

**ESTIMATING WATER USE AND YIELD OF SOYBEAN
(*GLYCINE MAX.*) UNDER MULCH AND FERTILIZER IN
RAINFED CONDITIONS IN KWAZULU-NATAL**

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PREFACE

The research contained in this dissertation was completed by the candidate while based in the Discipline of Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Water Research Commission Project Number K5/2491//4 titled ‘Water use of strategic biofuel feedstock’.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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DECLARATION: PLAGIARISM

I, Lungile Phumelele Lembede, declare that:

- (i) the research reported in this dissertation, except where otherwise indicated or acknowledged, is my original work;
- (ii) this dissertation has not been submitted in full or in part for any degree or examination to any other university;
- (iii) this dissertation does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;
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- (v) where I have used material for which publications followed, I have indicated in detail my role in the work;
- (vi) this dissertation is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;
- (vii) this dissertation does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the dissertation and in the References sections.

Signed: L.P. Lembede

Date:

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ABSTRACT

South Africa is classified as a semi-arid country characterized by low and erratic rainfall. This poses major limitations to crop productivity, especially for smallholder farmers who rely on rainfed agriculture. This is worsened by lack of knowledge regarding best management practices that can improve crop yields attained by smallholder farmers. In addition, smallholder farmers lack access to markets and do not participate in the agricultural value chain. The Biofuel Regulatory Framework (DoE, 2014) seeks to include smallholder farmers in the biofuel feedstock value chain. However, a prerequisite to their meaningful participation in the value chain would be to increase their current levels of crop and water productivity. The main aim of this study was to estimate the yield and water use of soybean (*Glycine max* L.) under rainfed and smallholder farming conditions using the AquaCrop model. Secondary to this, the effect of mulch and fertilizer on soybean water use efficiency was assessed. Lastly, the Soil Water Balance model (SWB) was used to compare simulations made by AquaCrop for the non-mulched, full fertilizer treatment. Thereafter, the water use efficiency of soybean was calculated from crop water use and the final yield. The soybean trial was carried out at Swayimane, KwaZulu-Natal. The model simulations of crop water use and reference crop evapotranspiration were also used to calculate crop coefficients under non-standard conditions. Crop growth and yield parameters were measured to calibrate and evaluate model performance. Soil water content was monitored using Watermark sensors, along with climatic variables. An analysis of variance (ANOVA) was used to detect significant interactions between treatments, while statistical indicators were used to evaluate model performance of AquaCrop and the SWB model. Mulching improved soil water content and reduced soil water evaporation, although the final yield and total water use efficiency was reduced. It is believed the yield reduction in mulched plots was mostly affected by nitrogen immobilization as a result of decaying straw mulch. Increasing soil fertility improved crop yield and water use efficiency in both mulched and non-mulched treatments. The AquaCrop model simulated the final yield and biomass fairly well, except in mulched treatments. The model simulated the highest yield in the mulched, fully fertilized plots, which is contrary to what was observed. This is because the model only accounts for improved soil water content and does not account for the complex interactions between the soil and mulch residue that resulted in nitrogen deficiency. The SWB model simulated fairly similar crop water use and yield to AquaCrop. The water use efficiencies obtained in this study were compared to that derived by Mengistu *et al.* (2014) for the same cultivar grown in a commercial farming environment at Baynesfield, KwaZulu-Natal.

In comparison to commercial farmers, smallholder farmers tend to produce lower water use efficiencies. The modelled water use efficiency reported for Baynesfield was 1.277 kg m^{-3} , compared to 0.359 kg m^{-3} obtained in this study for the non-mulched, full fertilizer treatment. According to AquaCrop, the mulched, full fertilizer treatment had a water use efficiency of 0.485 kg m^{-3} . It is believed that the latter water use efficiency could have been achieved had enough nitrogen been available to the crop. In conclusion, implementing best management practices can help narrow the yield gap between smallholder and commercial farmers. It was evident from this study and others that agronomic practices have a significant impact on crop yield and ultimately, water use efficiency.

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LIST OF ABBREVIATIONS

AWS	Automatic weather station
CC	Canopy cover
CSI	Campbell Scientific Inc.
DAFF	Department of Agriculture, Forestry and Fisheries
DIFN	Diffuse non-intercepted radiation
DME	Department of Minerals and Energy
DoE	Department of Energy
ET	Evapotranspiration
ET _o	Reference evapotranspiration
FAO	Food and Agriculture Organization
FC	Field capacity
GDD	Growing degree day
LAI	Leaf area index
NBIS	National Biofuels Industrial Strategy
K _{SAT}	Saturated hydraulic conductivity
PAW	Plant available water
PWP	Permanent wilting point
RETC	Retention curve utility
SAT	Saturation
SASRI	South African Sugarcane Research Institute
SPAW	Soil water characteristics calculator
SWB	Soil water balance model
TAW	Total available water
TPO	Total porosity
WRC	Water Research Commission
WUE	Water use efficiency

1. INTRODUCTION

Global demand for bioenergy is increasing due to different drivers across different regions. The use of biomass for energy production is attractive because it offers opportunities for exploiting renewable energy resources (Jewitt *et al.*, 2009). Biofuel is a liquid form of bioenergy and is defined as any renewable fuel that is derived from organic matter (DoE, 2014). It is mostly used in the transport sector by blending with petroleum fuel to achieve certain benefits. Some of the key drivers for biofuel production include reducing dependency on fossil-based fuels, reducing greenhouse gas emissions and economic development (DME, 2007). In developing countries such as South Africa, the predominant drivers of the biofuels industry are rural economic development, poverty alleviation and job creation, especially for smallholder farmers (DME, 2007). In the context of this study, smallholder farmer refers to historically disadvantaged, emerging and subsistence farmers who typically lack access to markets for their produce.

The liquid forms of biofuel are bioethanol and biodiesel. Bioethanol is obtained by the fermentation of sugar, or by the hydrolysis of starch or the degradation of cellulose followed by sugar fermentation and subsequently, distillation (Jewitt *et al.*, 2009; El Bassam, 2010; Janda *et al.*, 2012). Biofuel feedstocks are crops that are cultivated and undergo conversion processes for the production of biofuel (Jewitt *et al.*, 2009). Biodiesel is produced from plants that yield vegetable oil and can be blended with diesel derived from crude oil (Greiler, 2007). In theory, almost any crop can be used for biofuel production but the associated environmental, social and economic risks and benefits must be considered (Greiler, 2007).

This highlights the water-energy-food nexus which needs to be well managed in the biofuel value chain in order to ensure sustainability. An unresolved issue is whether feedstock production will reduce food security and thus, the approach in South Africa has been to exclude staple crops such as maize as potential biofuel feedstocks. Furthermore, the cultivation of biofuel feedstocks may decrease water availability to downstream water users.

Expansion of cultivated areas for biofuel feedstock production will demand resources such as land and water. Water scarcity and poor rainfall distribution in South Africa are already known to be major contributing factors to low crop yields. In 2002, the estimated water use by irrigation was 6 907 million cubic meters (m³), compared to 20 477 million m³ for dryland agriculture (Statistics South Africa, 2009). Therefore, the current under-estimation of water use

in dryland agriculture may have unforeseen consequences. However, irrigated agriculture currently accounts for the bulk of fresh water withdrawals (about 62%) in South Africa (FAO, 2016). The focus should therefore be on rainfed crop production with limited prospects for supplementary irrigation using groundwater and river abstractions during critical growth stages.

Soybean was specified as a reference feedstock to represent oil crops for biodiesel production in the Biofuel Regulatory Framework (DME, 2007), since it is believed to be economically feasible. Two biofuel manufactures have proposed the annual production of 458 ML of biodiesel from soybean and 500 ML from canola. Canola is not considered a feasible crop to grow in KwaZulu-Natal due to unfavourable growing conditions in this region (Whitehead, 2010; cited by Sparks, 2010). Furthermore, the proposed biofuel manufacturer may also import canola and thus, information on soybean yield and water use is deemed more valuable (van Rooyen, 2013; cited by Khomo, 2014).

Grain sorghum was also identified in the Biofuel Regulatory Framework as a reference crop to represent starch crops for bioethanol production. The crop was selected as a strategic feedstock since it would require the least financial subsidy. This realisation was based on price forecasts of grain sorghum and sugarcane (DME, 2007). An additional advantage of grain sorghum is that it uses less water than sugarbeet (DME, 2007), although research presented by Kunz *et al.* (2015) disagrees with this finding. In this study, soybean was selected as the crop of interest over grain sorghum due to a lack of information in the literature regarding water use of soybean in rainfed, smallholder conditions. Furthermore, soybean is currently grown in large quantities (Khomo, 2014) and hence, the necessary experience for expansion is available. On the contrary, the area under grain sorghum cultivation is declining as a result of improving maize prices (Khomo, 2014). Additionally, a total of 458 ML an⁻¹ of biodiesel is to be produced from soybean while only 248 ML an⁻¹ of bioethanol will be produced from grain sorghum (*cf.* **Table 2.1**). As discussed in more detail in **Section 2.2.1**, oil cake is a by-product of soybean used for animal feed. This places more value on soybean. In fact, it is worth noting that the soybean plant in Port Elizabeth will be used to produce oil cake as the primary product and biodiesel as the by-product (Payne, 2013 cited by Khomo, 2014). Therefore, there is a greater need to quantify the water use efficiency of soybean over grain sorghum for the above-mentioned reasons which place more emphasis on soybean as a potential feedstock than compared to grain sorghum.

According to DME (2007), land availability is not considered a limiting factor to biofuel feedstock production. However, smallholder farmers mostly reside in marginal agricultural production areas (Tittonell and Giller, 2013). Rainfall variability is one of many factors that make these areas marginal. Hence, variability of rainfall over the crop growing season challenges the feasibility of smallholder farmers' participation in the biofuel supply chain, since they already struggle to produce meaningful yields. For smallholder farmers, the impacts of low water availability are further exacerbated by marginal land and poor agronomic practices as well as lack of capital which further curtail crop yields. Therefore, in order for smallholder farmers practising rainfed agriculture to benefit from biofuel production, there is a need to improve their agronomic practices to increase yields under limited water availability, i.e. by improving water use efficiency, which relates crop yield to crop water use.

Under rainfed systems, water scarcity and low observed yields have highlighted the importance to improve water use efficiency for improved productivity. Water use efficiency is mainly affected by agronomic practices which influence the crop yield (i.e. planting density, crop water availability, fertilization, weed management as well as pest and disease management). For example, all else being equal, crop yield is likely to be higher in fertilized soil compared to nutrient deficient soil and therefore, crop water use efficiency will be higher. It is important to understand the water use characteristics of potential biofuel feedstocks in order to maximize crop productivity and water use efficiency, which will ensure sustainable feedstock production. The challenges experienced by smallholder farmers need to be understood as they are expected to be different to the challenges typically faced by commercial farmers due to differences in, *inter alia*, economies of scale. Participating in the biofuel value chain could also offer meaningful opportunities for escaping poverty and employment creation within rural areas. To this end, the South African Biofuel Regulatory Framework (DoE, 2014) aims to improve economic development and poverty alleviation, especially for previously disadvantaged emerging farmers in rural areas.

Therefore, an understanding of agronomic practices that optimise water use efficiency is central to the viability and feasibility of smallholder participation in the biofuel value chain. The literature showed that the most influential factors affecting crop yields in smallholder farming conditions are soil water availability and soil fertility. Therefore, the effects of mulch and fertilizer application on water use efficiency of soybean were selected as the agronomic practices to be tested in this study. The AquaCrop model, developed by the Food and Agricultural Organization (Raes *et al.*, 2009), was used to simulate water use efficiency under

all treatments. Hence, this model can account for the influence of the specified agronomic practices on crop yield. In addition, the SWB model (Jovanovic and Annandale, 2000) was used to simulate water use efficiency under the control treatment, since it does not account for varying soil fertility levels and mulching. The simulation of water use efficiency by both models were then compared. It is important to note that the soybean seed was not inoculated in order to keep the trial as representative of smallholder farming conditions as possible. Smallholder farmers generally avoid seed inoculation as they fail to understand the concept of nitrogen fixation and hence, the benefits of seed inoculation (Mabhaudhi, 2015; personal communication).

1.1 Aims and Objectives

The main research question to be addressed in this study was: “Can smallholder farmer yields (and subsequently, water use efficiency) be improved by implementing best management practices (i.e. soil water and soil fertility management)?” Therefore, the focus of the study was on modelling crop water use, crop yield and determining water use efficiency under mulching and soil fertility management in order to answer the research question. It was hypothesized that implementing best management practices would improve crop yield and soil water availability and hence, the overall water use efficiency. The field based measurements contributed to the calibration and validation of the AquaCrop and SWB models. The results obtained in this study will help to develop best management practices for smallholder farmers. The specific objectives of this study were to:

- determine the effect of mulching and soil fertility on water use and yield of soybean,
- derive crop coefficients of soybean grown under rainfed conditions,
- compare soybean’s water use efficiency under smallholder farming conditions with that for a commercial farm in order to quantify the yield gap between smallholder and commercial farmers. Such information may emphasize the need to improve crop yields under smallholder farming conditions by adopting best management practices, such as those adopted by commercial farmers.
- to calibrate the AquaCrop model (Raes *et al.*, 2009; Steduto *et al.*, 2009), and finally,

- model water use and yield of soybean under rainfed conditions using the AquaCrop model and compare the control treatment (no mulching, fully fertilized) against simulations from the SWB model.

1.2 Structure of Dissertation

The structure of the dissertation is such that a review of policy related to the production of biofuel is given (*cf.* **Section 2.1**), which focuses on a) 2007 National Biofuel Industrial Strategy, and 2) the Biofuel Regulatory Framework of 2014. Factors affecting crop water use and yield (effectively, WUE) are reviewed next (*cf.* **Section 2.3**). The literature review is concluded with a discussion of the modelling component (*cf.* **Section 2.4**) and a brief summary of the study (*cf.* **Section 2.5**).

Thereafter, the materials and methods adopted in the study are explained and justified (*cf.* **Section 3**). This section also includes a description of the soybean cultivar used, the study site, as well as data acquisition in both the field and laboratory. Finally, the soybean field trial measurements are linked to the modelling component. The results and discussion present the results and an interpretation thereof (*cf.* **Section 4**). Finally, conclusions and recommendations are made based on findings with regard to favourable agronomic practices (*cf.* **Section 5**).

2 LITERATURE REVIEW

Biofuel-related policy in South Africa is discussed below, beginning with a brief description of the National Biofuel Industrial Strategy (NBIS) released in 2007 (DME, 2007). The shortcomings of the document are discussed, leading up to the development of the Biofuel Regulatory Framework (DoE, 2014), with the objective of effectively implementing the NBIS. Finally, the inclusion of smallholder farmers, through policy implementation and incentives is discussed.

2.1 The Biofuel Industry in South Africa

It is believed that South Africa has potential to successfully produce biofuel feedstock since there is a significant portion of uncultivated land that is suitable for rainfed agriculture (Greiler, 2007; Molden *et al.*, 2010). The NBIS was developed in order to promote biofuel production to help target poverty alleviation through job creation, expansion of agricultural production and rural economic development. The aim of the NBIS is to help stimulate economic activity, especially in the former homeland areas. In the context of this study, the former homelands refer to under-utilisable arable land in the provinces of Limpopo, North West, Eastern Cape and KwaZulu-Natal (DME, 2007). The Biofuel Regulatory Framework (DoE, 2014) does not encourage the conversion of current commercial farmland to feedstock production in order to ensure that food security is not threatened by biofuel feedstock production. Furthermore, certain crops have been excluded for participation in the biofuel value chain (such as maize) so as to ensure food security. The Biofuel Regulatory Framework (DoE, 2014) encourages smallholder farmers to produce biofuel feedstock under rainfed conditions on under-utilized land and thus, serves as a guideline for this study.

2.1.1 The National Biofuel Industrial Strategy of 2007

The goal of the NBIS was to achieve a 2% blending target of biofuel with fossil-based fuel over a period of five years (DME, 2007). However, this short-term goal was not achieved due to lack of investment in the industry because biofuel production is less financially attractive at current crude oil prices (Sparks, 2010; WRC, 2014). Hence, policy regulations and incentives need to be implemented in order to establish this emerging industry. The critical success factors of the biofuel industry as identified by Sparks (2010), include overcoming economic barriers that are associated with competition with fossil fuels. Apart from direct policy regulations, the most significant driver of biofuel use is the price ratio between biofuels and fossil fuels

(Donburg *et al.*, 2010). The above-mentioned shortcomings on the NBIS have been addressed by the Biofuel Regulatory Framework, which is discussed next. According to the Biofuel Regulatory Framework, the feedstocks that will be used for biodiesel production are soybean, canola and sunflower (grain sorghum, sugarbeet and sugarcane for bioethanol).

2.1.2 The Biofuel Regulatory Framework of 2014

The Biofuel Regulatory Framework (DoE, 2014) provides a more conducive framework for biofuels up-take. The Biofuel Regulatory Framework has more effective implementation strategies through, *inter alia*, pricing policy regulation, mandatory blending of petrol with biofuel and licensing of biofuel producers. The Biofuel Regulatory Framework provides a conducive environment for participation in the biofuel industry by enforcing policy regulations and incentives that were not effectively enforced in the NBIS (Molden *et al.*, 2010). The proposed policy regulations in the Biofuel Regulatory Framework include mandatory blending of biofuels with fossil fuel, contractual obligations between petroleum companies and biofuel producers to ensure assurance of supply as well as the licensing of biofuel producers (DoE, 2014). The details of biofuel processing plants that have been issued (applicants possess a manufacturing licence) or granted (applicants possess a conditional manufacturing license) are shown in **Table 2.1**.

Table 2.1: Licence applications that have been processed by the Controller of Petroleum Products for biofuel production (Source: DoE, 2014)

Company	Biofuel	Feedstock	Capacity ML/an	Location	License
Mabele Fuels	Bioethanol	Sorghum	158	Bothaville, FS	Issued
		Sorghum/			
Arengo 316	Bioethanol	Sugarbeet	90+90	Cradock, EC	Granted
Ubuhle RE	Bioethanol	Sugarcane	50	Jozini, KZN	Issued
			388		
Phyto Energy	Biodiesel	Canola	500	Port Elizabeth, EC	Applying
Rainbow					
Nation	Biodiesel	Soybean	288	Port Elizabeth, EC	Issued
Basfour	Biodiesel	Soybean	170	Berlin, EC	Issued
			958		

The approved capacity of total biofuel production far exceeds the targeted 2%, or 400 million litres (ML) and the implication of this on the country's scarce water resources is concerning. The main crops that have been selected by biofuel producers, i.e. soybean, canola and grain sorghum are reviewed in this study (*cf.* **Section 2.2**). However, as discussed in **Section 2.2.1**, soybean was used to carry out a field trial. Soybean was selected as the reference crop to determine the incentive required for biodiesel production. Hence, information on crop water use and yield is important to help implement the framework.

According to the Biofuel Regulatory Framework (DoE, 2014), the policy regarding mandatory blending of fuels was meant to take effect in October 2015. However, this goal was not achieved. The biofuels pricing framework needs to be finalized before effective implementation of the biofuels industrial strategy. Hence, there is still uncertainty regarding when the biofuels pricing framework will be released. Regardless of whether or not the implementation of the industrial strategy will eventually be implemented, studies regarding crop water use efficiency remain relevant for advising smallholder farmers about more sustainable crop management practices to achieve higher crop yields.

2.1.3 Role of smallholder farmers

In order to improve agricultural production in the former homelands, government support will be provided to emerging farmers to encourage interest in the biofuels industry until a 2% penetration level in the initial development stages is reached (i.e. over a five-year period) (Brent, 2014). During the implementation phase, local crops grown by emerging farmers will be eligible for the producer support scheme. The stimulation of economic activity in previously disadvantaged areas will be ensured by the following proposed policy regulations:

- A minimum of 10% of biofuel feedstocks will be sourced from the combination of emerging, smallholder and previously disadvantaged farmers within four years of plant manufacturing operations (DoE, 2014).
- Manufacturing plants must be owned and controlled by a minimum 25% of previously disadvantaged farmers (DoE, 2014).
- Additionally, all investors in the biofuel industry will be supported until reasonable returns on investments are made (DME, 2007). The support services include incentives for biofuel production and especially for emerging farmers, as well as education on production methods for obtaining higher crop yields.

2.2 Feedstock for Biofuel Production

The selection of feedstock determines the profitability of biofuel production (El Bassam, 2010). It is imperative to ensure sustainable biomass production which can be achieved by, *inter alia*, the selection of appropriate cultivars for various locations and to consider plant population density as well as uniform plant spacing (Du Plessis, 2008; Ritchie and Basso, 2008; Sparks, 2010). In addition, different water requirements exist in the various growth stages of the crop and thus, it is important to understand when water supply is crucial for maximising growth (Molden *et al.*, 2010). In this study, only the main crops whose production had been proposed by biofuel manufactures were reviewed (i.e. soybean, canola and grain sorghum). A brief description of each crop is given, followed by agro-ecological and agronomic requirements that favour optimal crop growth. The climatic parameters for optimal growth for each crop are presented in **Appendix 1**.

2.2.1 Soybean

The soybean plant belongs to the *Fabaceae* family and originates from China (El Bassam, 2010). The fruit of the plant develops in the form of pods, in which three seeds are usually found (El Bassam, 2010). The genetically modified version of the soybean plant (i.e. the Roundup® ready cultivar), can survive being sprayed by Roundup®, which is a non-selective herbicide containing glyphosate (El Bassam, 2010). Soybean has many uses in the food, feed and energy industries. Soybean oil can be extracted from soybean and can be used for cooking and other edible uses by humans, such as soymilk, tofu, margarine and soy-based yoghurts (Mpepereki *et al.*, 2000). Soybean oilcake is a by-product derived from soybean and is valuable for animal feed (Sparks, 2010). Furthermore, soybean oil can be used in the energy sector by producing biodiesel.

Soybean has been identified in the Biofuel Regulatory Framework as a strategic feedstock to represent biodiesel production. This selection was made on the basis of economic feasibility of soybean production when it is incentivised. Soybean also has a high animal feed value by-product. Sparks (2010) suggested that investment into small-scale oil crushing facilities would be a more economically viable option.

According to DAFF (2010a), soybean production has been in the range of 450-500 thousand tons per annum. Sihlobo and Kapuya (2016) report that the production of soybean reached 1 million tons in the 2015/16 season. This increase in production is believed to result from the

investment in soybean crushing capacity to decrease imports of soybean oil and oil-cake into South Africa. Since the crop is locally grown, the necessary experience for expanded production of soybean exists. However, expansion of land under soybean cultivation is expected to have an impact on water resources. The significance of the impact of the area under soybean cultivation on water resources should be estimated in order to ensure informative decision-making.

DAFF (2010a) reported an average yield of 2.5 to 3 t ha⁻¹ of soybean under rainfed conditions. Mengistu *et al.* (2014) obtained a yield of 3.5 t ha⁻¹ in a commercial environment, where supplemental irrigation was used. However, Schulze and Maharaj (2006; cited by Jewitt *et al.*, 2009) reported a national average of 1.6 to 1.7 t ha⁻¹, which is believed to be more representative of smallholder farming conditions, although it is much lower than the yield reported by DAFF (2010a). Global trends of soybean yields include the yields of 0.2 to 0.4 t ha⁻¹ in Tanzania, 2.16 t ha⁻¹ in Georgia, 2.59 t ha⁻¹ in the USA and 3.6 t ha⁻¹ in Italy (Oerke and Dehne, 2004).

Although soil water availability affects crop yield, of more importance is the availability of soil water during vital crop growth stages. This concept is best explained by the concept of crop coefficients, which indicates crop water use at different crop growth stages. Jewitt *et al.* (2009) reported on crop coefficient values of soybean based on FAO values, which are internationally derived. (*cf.* **Table 2.2**). However, Kunz *et al.* (2015) reported crop coefficient values derived from local conditions in Baynesfield from measurements of water use done by Mengistu *et al.* (2014). Monthly crop coefficients derived from Baynesfield were estimated under dryland, relatively non-stressed conditions.

Table 2.2: Crop coefficient values based on FAO values and local conditions

Jewitt <i>et al.</i> (2009)		Kunz <i>et al.</i> (2015)	
Crop growth stage	Crop coefficient	Month	Crop coefficient
Initial	0.3-0.4	November	0.72
Development	0.7-0.8	December	0.72
Mid-season	1.0-1.15	January	1.00
Late	0.7-0.8	February	1.03
Harvest	0.4-0.5	March	0.84

2.2.2 *Canola*

The scientific name for canola is *Brassica napus* L., belonging to the *Brassicaceae* family and originates from Canada (Faraji *et al.*, 2009). The current distribution of canola is restricted to

temperate and sub-temperate regions (Jewitt *et al.*, 2009). In South Africa, canola is mainly grown in the southern regions of the Western Cape as a winter crop (DAFF, 2014). Although Phyto Energy have proposed to produce 500 ML of biodiesel from canola, this crop is not grown in large quantities in KwaZulu-Natal, mostly because of unfavourable growing conditions (Whitehead 2010; cited by Sparks, 2010). Furthermore, according to van Rooyen (2013), Phyto Energy may import canola. Canola is primarily used to produce oil, oil cake and canola meal (DAFF, 2014). The Western Cape accounts for 98% of the country's production of canola (DAFF, 2014). The canola industry has been experiencing prices fluctuations in the past ten years as a result of limited production in South Africa (DAFF, 2014). As a result, South Africa has been a net importer of canola.

2.2.3 Grain sorghum

Grain sorghum belongs to the *Poaceae* family (FAO, 2013a) and is indigenous to Africa (Swanepoel, 2006). Grain sorghum consists of broadly roundish grain, with stem growth reaching up to 4 m (FAO, 2013a). It is an important cereal crop that has multiple uses including ethanol production (Gou *et al.*, 2011), malt, beer, beer powder, sorghum meal, sorghum rice and other animal products (Swanepoel, 2006). Grain sorghum can survive marginal soil conditions (i.e. low potential, shallow and high clay content) and has been cultivated by smallholder farmers as a subsistence crop (Mabele Fuels, 2017). However, the current yield of grain sorghum in smallholder conditions is not known (DAFF, 2010b), although Duze *et al.* (2007) report that average yields remain below 1 t ha⁻¹ due to poor agronomic practices. To date, there has been little research on the performance of sorghum varieties in the production of ethanol (Wang *et al.*, 2008). Mabele Fuels have chosen grain sorghum to meet the requirements of the Biofuel Regulatory Framework as they believe that a secured demand of the crop may potentially help smallholder farmer's progress to commercial farmers (Mabele Fuels, 2017). Furthermore, an advantage of grain sorghum is that it can be grown in drier areas and is not water intensive (Mabele Fuels, 2017).

2.2.4 Summary

Soybean was identified in the Biofuel Regulatory Framework (DoE, 2014) as a strategic feedstock due to its' economic feasibility and its' high value by-product. The area under soybean cultivation has recently increased due to oilcake crushing ventures. Two biofuel manufacturers are planning to produce a total of 458 ML of biodiesel from soybean (*cf.* **Table 2.1**). For sustainable production, optimal crop yields must be obtained. Furthermore, there is

need to quantify the water use and crop yield of soybean under rainfed conditions in order to determine the impact of agricultural expansion on the country's scarce water resources. Soybean was therefore selected as the appropriate crop for the field trial experiment in order to investigate the effects of agronomic practices on crop water use and yield. Additionally, water use efficiency data for soybean grown in a commercial farming environment in the 2012/13 season, as reported by Kunz *et al.* (2015), will facilitate the comparison of figures obtained in this study for smallholder farming conditions.

2.3 Crop Water Use Efficiency

The global demand for domestic and industrial freshwater is constantly increasing due to population and economic growth (Ritchie and Basso, 2008). Additionally, with an average rainfall of approximately 450 mm (Lynch, 2004), South Africa is considered as a semi-arid country. According to Palmer and Ainslie (2006), semi-arid regions are characterised by low average annual rainfall (401 - 600 mm), high temperatures and a crop growing period ranging from 70 to 180 days, with the rest of the year having higher evaporation than precipitation (Fischer *et al.*, 2009). These growing conditions have adverse implications on rainfed agriculture as water availability for plant growth is limited and unreliable. With limited water resources, efficient water use in agriculture is essential to maximize agricultural productivity (Gheewala *et al.*, 2011). Improving water use efficiency (WUE) means that higher crop yields should be obtained using less and/or the same amount of water, i.e. 'more crop per drop'. This can be achieved by ensuring that available water is used productively in a way that favours biomass accumulation and yield maximisation. Improving WUE can help contribute to economic growth and poverty reduction by narrowing yield gaps (Janda *et al.*, 2012).

Smallholder farmers produce lower crop yields and subsequently they experience lower WUEs when compared to commercial farmers. The difference in yields obtained by smallholder and commercial farmers is caused by agricultural inputs, resources and knowledge that is more easily accessible by commercial farmers. Although water scarcity and poor rainfall distribution are a major causes of low crop yields, other factors play a role. When sufficient water is available for vegetative growth, persistent yield gaps are attributed to poor agronomic practices (Fanadzo *et al.*, 2010). In the context of this study, a yield gap refers to the difference between actual and potential yield. Lack of knowledge regarding best management practices, insufficient resources and poor support from extension officers are believed to contribute to low water use efficiencies experienced in smallholder farming systems (Mendesil *et al.*, 2007;

Azadi and Ho, 2010; Fanadzo *et al.*, 2010; Rossi, 2012). Knowledge regarding the causes of yield gaps can help to efficiently target efforts to improve crop production and narrow yield gaps (Lobell *et al.*, 2009). The concept of water use efficiency is explained below. Furthermore, the factors that affect water use efficiency are discussed and how these can be managed in order to maximize the crop yield.

2.3.1 Definition of water use efficiency

In the context of this study, WUE refers to the crop yield produced per unit amount of water used by the crop and is expressed as:

$$WUE = \frac{Y}{ET} \quad \text{Equation 2.1}$$

where Y = crop yield (kg) and

ET = actual crop evapotranspiration (m^{-3}).

Crop water use refers to water lost through crop transpiration, soil water evaporation and canopy interception (Kunz *et al.*, 2015). These three processes occur simultaneously and are difficult to measure separately. Interception is the portion of water lost when the canopy or crop residue retains precipitation which then evaporates into the atmosphere without recharging the soil's water content. Transpiration is the transfer of water vapour from plants to the atmosphere, whereas soil water evaporation is the transfer of water vapour from the soil surface to the atmosphere (Molden *et al.*, 2010). Transpiration is considered to be a productive use of water since higher transpiration results in higher biomass production and subsequently, higher crop yield. On the other hand, soil water evaporation is considered an unproductive loss because it reduces soil water that would otherwise be used for transpiration. The rate of soil water evaporation depends on how much soil surface is exposed to incoming solar radiation (Mampana, 2014). It typically declines as the crop develops and shades more of the soil surface. Hence, transpiration is related to canopy cover, whereas soil water evaporation is proportional to the area of uncovered soil (Voloudakis *et al.*, 2015).

Stomatal conductance measurements provide insight into crop transpiration. Stomatal conductance is the measure of the diffusion of carbon dioxide into and water vapour out of the leaf (Mabhaudhi, 2012). When stomata are open, carbon dioxide flows into the leaves and water vapour is released (Molden *et al.*, 2010). This process facilitates crop photosynthesis.

Additionally, the outflow of water vapour is necessary for cooling the plant and mobilizing soil nutrients. Stomatal conductance is reduced under water-limiting conditions, thereby limiting transpiration and photosynthesis, which may affect biomass production (Molden *et al.*, 2010). When leaves fail to maintain turgor as a result of severe water stress, temporary wilting occurs. If the crop is watered or the evaporative power of the atmosphere is reduced, turgor can be restored, failing which the plant wilts permanently (White, 2003).

Stomatal conductance is affected by climatic conditions, such as solar radiation, relative humidity, carbon dioxide concentration, soil water content and physiological conditions within the plant (Jones and Higgins, 1989). Zhao *et al.* (2005) also reported that stomatal conductance is affected by nitrogen deficiency.

By definition, another factor that influences WUE is the crop yield. Crop yields can be improved by genetic modifications and appropriate land management practices (Donburg *et al.*, 2010; Greiler, 2007). There is much potential for yield improvements by smallholder farmers as their yields are much further from the exploitable yield. The exploitable yield gap describes the difference between 80% of the potential yield and the actual yield (Lobell *et al.*, 2009). The exploitable yield may be achieved by commercial farmers but smallholder farmers are likely to achieve only half of the exploitable yield due to the above-mentioned limiting factors (Lobell *et al.*, 2009).

Crop yields can be improved by implementing the appropriate agronomic practices. Similarly, WUE can be increased by implementing agronomic practices that improve soil water availability, such as mulching. Theoretically, this should improve crop transpiration, which is directly proportional to biomass accumulation. Other factors affecting WUE are discussed below, including a comparison between commercial and smallholder farming conditions

2.3.2 Factors affecting water use efficiency

The predominant factors that affect crop yield and hence WUE vary across different regions. The factors affecting WUE can be categorised into biotic (living) and abiotic (non-living) factors (**Table 2.3**).

Table 2.3: Environmental factors affecting crop yield and water use, as well as various farm management practices to help buffer the impacts (adapted from Oerke, 2006; Ritchie and Basso, 2008).

Abiotic factors	Mulching	Cultivar choice	Planting date	Planting density	Crop rotation	Other
Soil fertility	yes			yes	yes	Intercropping
Radiation	yes	yes	yes	yes		Seeding depth
Temperature	yes	yes	yes	yes		Irrigation
Soil water availability	yes	yes	yes	yes	yes	Soil water
Soil nutrient status				yes	yes	Fertilizer
Biotic factors						
Weeds	yes	yes	yes	yes	yes	Herbicide; cover crops
Insect pests		yes	yes		yes	Pesticide
Plant diseases		yes	yes	yes	yes	Fungicide; bactericide
Animals and birds		yes				Fencing; netting; trap crops

Note: The abiotic and biotic factors are listed, along with an indication (yes) of land management/agronomic impacts that can be implemented in order to effectively manage the impacts of each factor

For the purpose of this study, the focus is on abiotic factors rather than biotic factors which are commonly the most difficult to manage. This is due to the lack of knowledge on best land management practices that can be implemented to manipulate these factors so that the desired outcome is achieved. The most problematic factors in smallholder farming conditions were identified as soil water availability, soil fertility and weed management. This study focused specifically on soil water availability and soil fertility. Weed management was excluded as the primary crop model (i.e. AquaCrop) used in this study can only account for the impact of mulching and soil fertility on water use efficiency (*cf.* **Section 2.4.1**). The impact of mulching and soil fertility on crop yield as a means to improve soil water availability and soil nutrient status is discussed below.

2.3.2.1 Soil water availability

Soil physical properties affect the amount of soil water that is available to use by the crop. Soil texture affects soil porosity, hence the amount of water that can be stored in the soil over a period of time. A soil with greater sand particles has a greater saturated hydraulic conductivity, meaning more water is drained than is retained over time. This implies less water is available for use by the crop. Furthermore, soil water retention characteristics, such as total porosity, total available water, field capacity and permanent wilting point affect crop soil water availability (discussed in more detail in **Section 3.5.4**).

The most important and problematic factor that hinders optimal agricultural production in rainfed agriculture is low soil water availability (Molden *et al.*, 2010). Soil water availability is affected by, *inter alia*, soil water evaporation, which can be reduced by implementing simple practices that aim to shade the ground, e.g. higher plant population density and crop breeding to enhance leaf expansion (Ritchie and Basso, 2008). In rainfed crops, mulching and rainwater harvesting can also be used to improve soil water availability. On-farm by-products such as wheat straw, leaf debris and grass clippings can be used as mulch (Mc Millen, 2013). However, the high demand of crop residue for other uses (e.g. animal feed, especially during winters and building material) in Sub-Saharan Africa discourages the adoption of mulching (Giller *et al.*, 2009). Other potential sources of mulch are plastic sheets (Raes *et al.*, 2009), sawdust (Sinkevičienė *et al.*, 2009), and gravel (Rossi, 2012). According to Ren *et al.* (2010), mulching can improve soil moisture content in the root zone, which in-turn can result in significant yield gains in areas that experience low rainfall. Mulching the soil surface with crop residues has other benefits which include:

- lowering soil temperature and soil water evaporation by reducing the amount of absorbed radiant energy (Marshall and Holmes, 1988),
- increasing water infiltration and subsequently soil water content (Ren *et al.*, 2010),
- moderating soil temperature extremes (Mashingaidze, 2013) since straw mulch has low thermal conductivity, thereby suppressing heat exchange between the soil and atmosphere (Ren *et al.*, 2010),
- improving soil structure by increasing aggregate stability (Rossi, 2012); and
- reducing soil erosion (Pannell *et al.*, 2014).

However, the use of organic mulches can result in reduced nitrogen availability caused by the decomposition of the mulch containing a high C:N ratio (Neuweiler *et al.*, 2003; Sønsteby *et al.*, 2004; Siczek and Lipec, 2011). Prolonged immobilization of nitrogen may result in nitrogen deficiency, which results in yellowing of older leaves and stunted growth of soybean (ASGROW, 2015). Furthermore, negative crop yield responses may be experienced in humid and cooler climates, where soil moisture and average temperatures are adequate for crop growth and development (Olivier and Singels, 2015). This is because where soil moisture is available, mulch residue can increase soil water further, and this may lead to anaerobic soil conditions, which may have adverse impacts on the crop yield. Where the soil surface temperature is favourable, mulch residue can reduce the soil surface temperature to sub-optimal temperatures, thereby affecting crop yield. Additionally, mulches may retard seed germination and early plant growth (Hillel, 1998).

2.3.2.2 Soil fertility

Soil fertility is the ability of the soil to provide adequate amounts of minerals and nutrients to facilitate plant growth and development. A major cause for low crop yields for smallholder farmers is the application of inadequate amounts of fertilizers, accompanied by poor timing of fertilizer application (Molden *et al.*, 2010). Nitrogen (N), Phosphorous (P) and Potassium (K) are known as the main macronutrients since they are required in larger amounts than compared to Sulphur (S), Calcium (Ca) and Magnesium (Mg), which are the secondary macronutrients (Dinkins and Jones, 2013).

Nitrogen is a vital component of chlorophyll, which is responsible for plant photosynthesis (IFA, 1992). It is a component of amino acids that make up proteins which are responsible for essential biochemical reactions (Ohyama, 2010). Furthermore, nitrogen is a component of DNA (deoxyribonucleic acid), which allows cells to multiply and reproduce as well as ATP (adenosine triphosphate), which allows cells to store and use energy (Ohyama, 2010). Nitrogen is available to plants as nitrates (NO_3^-) and ammonium (NH_4). Although legumes such as soybean are known to fix atmospheric N, previous research has shown that in degraded soils, a starter dose of N is required before the benefits on the N fixation process are realized (Giller, 2003). Or else the seeds should be inoculated with the *Bradyrhizobia japonicum* bacteria (Moore *et al.*, 1994), which are responsible for the N-fixing process (Aniekwe and Mbah, 2014). These bacteria are in a symbiotic relationship with the crop where they transform atmospheric nitrogen (N_2) into its readily available form (NH_4), while the crop provides carbohydrates to the bacteria in return (ASGROW, 2015). If soil N supply does not meet the

demand by the crop, the N will be remobilized from the leaves to the grain, thereby diminishing the photosynthetic capacity of the canopy (Salvagiotti *et al.*, 2008).

Phosphorous in the soil is highly immobile and is therefore less readily available for plant uptake (Dinkins and Jones, 2013). Phosphorous enhances several functions of the plant including the rate of photosynthesis, enzymatic activity, energy transfer, the uptake and transfer of certain nutrients, N fixation and nodulation, reproductive growth, seed number and seed germination (Snyder, 2000).

Potassium can be continuously absorbed by plants, even beyond yield requirements. Therefore, it is important to test for nutrient availability to reduce loss from over-fertilization (Dinkins and Jones, 2013). Potassium is highly mobile and as a result, can be leached from crop litter or surface residues into the soil solution (Heidari and Jalili, 2016). Potassium regulates plant processes such as water and nutrient transport, regulation of water vapour and carbon dioxide through stomatal control as well as the uptake and transfer of certain plant nutrients (Snyder, 2000).

2.3.3 Biofuel use efficiency

Kunz *et al.* (2015) defined the term “biofuel use efficiency” as the theoretical biofuel yield (in L) per unit of water use (in m³). Biofuel use efficiency is affected by the actual seed yield since the biofuel oil is extracted from the seed. Therefore, where low yields are experienced, low biofuel efficiency is likely to occur.

Seed quality affects the amount of oil that can be extracted from the seed. Higher quality seeds are believed to have higher seed oil content. Various experiments have been conducted to test the effects of management practices in order to better understand the impact of management on seed oil content.

Such experiments tested the impact of fertility, seed inoculation, and temperature effects as a function of planting date and row spacing. Although soybeans require little or no nitrogen fertilizer, phosphorous is essential for high yields and improved seed quality (Malik *et al.*, 2006). Tanwar and Shakwat (2003) and Win *et al.* (2010) observed an increase in seed oil content with increasing phosphorous application. Potassium has also been reported to improve crop yield and seed quality (Sawan *et al.*, 2006; Mokoena, 2013). Additionally, significant seed oil content responses have been reported due to the interaction of increased levels of both phosphorous and potassium (Borges and Mallarino, 2000).

Other management factors (e.g. seed inoculation) have improved seed oil content (Malik *et al.*, 2006). Research on row spacing and applied irrigation has shown that these two practices have an impact on seed oil content (Bellaloui *et al.*, 2015b). Additionally, early planting resulted in higher oil content, indicating an influence of temperature on seed oil content (Bellaloui *et al.*, 2015a).

2.4 Modelling of Crop Yield and Water Use

Crop simulation models can be used to understand crop response to water stress and various management practices (Farahani *et al.*, 2009). They provide helpful tools to identify management practices that affect water use efficiency (Saab *et al.*, 2015). The basis of crop simulation models is described by Todovoric *et al.* (2009) as a set of equations that simulate biomass production via three different growth engines, *viz.*:

- water-driven: simulates biomass production from accumulated transpiration using a linear relationship and a water productivity parameter (e.g. AquaCrop or SWB model),
- radiation-driven: simulates crop growth from incoming solar radiation via radiation use efficiency coefficient that incorporates the intermediary steps contributing to biomass accumulation (e.g. SWB model), and
- carbon-driven: crop growth is based on the absorption of carbon by the leaves through photosynthesis and respiration.

Since different crop simulation models exist, the most appropriate model needs to be selected based on the scope and intention of the study (Vanuytrecht *et al.*, 2014). A crop model that is sensitive to the primary management factors that affect crop yield can be used to provide an insight into the impact of various management practices on crop yield (Ritchie and Basso, 2008). For this study, the AquaCrop model was selected as the most appropriate model due to its suitability to water-limited environments as well as its ability to simulate the effects of soil fertility and mulching on crop growth and yield.

On the contrary, the Soil Water Balance model (or SWB) model is either radiation or water driven (depending on the most limiting resource), but does not account for the effects of mulch and soil fertility. The SWB model was used to simulate crop water use and yield made for the control treatment (i.e. non-mulched, fully fertilized treatment). The results of both models were compared to observed data. A brief description of each model is given below.

2.4.1 The AquaCrop model

The AquaCrop model (Raes *et al.*, 2009; Steduto *et al.*, 2009) is a crop water productivity simulation model that was developed by the Food and Agricultural Organisation (FAO). In comparison to other crop models, AquaCrop is based on a water-driven growth engine (*cf.* **Figure 2.1**) which is most effective in areas where water is a limiting factor to plant growth (Voloudakis *et al.*, 2015). Additionally, the model requires few input parameters that can easily be obtained from field observations (Todovoric *et al.*, 2009). Furthermore, the model can be used to address both the impact of soil water availability and soil fertility.

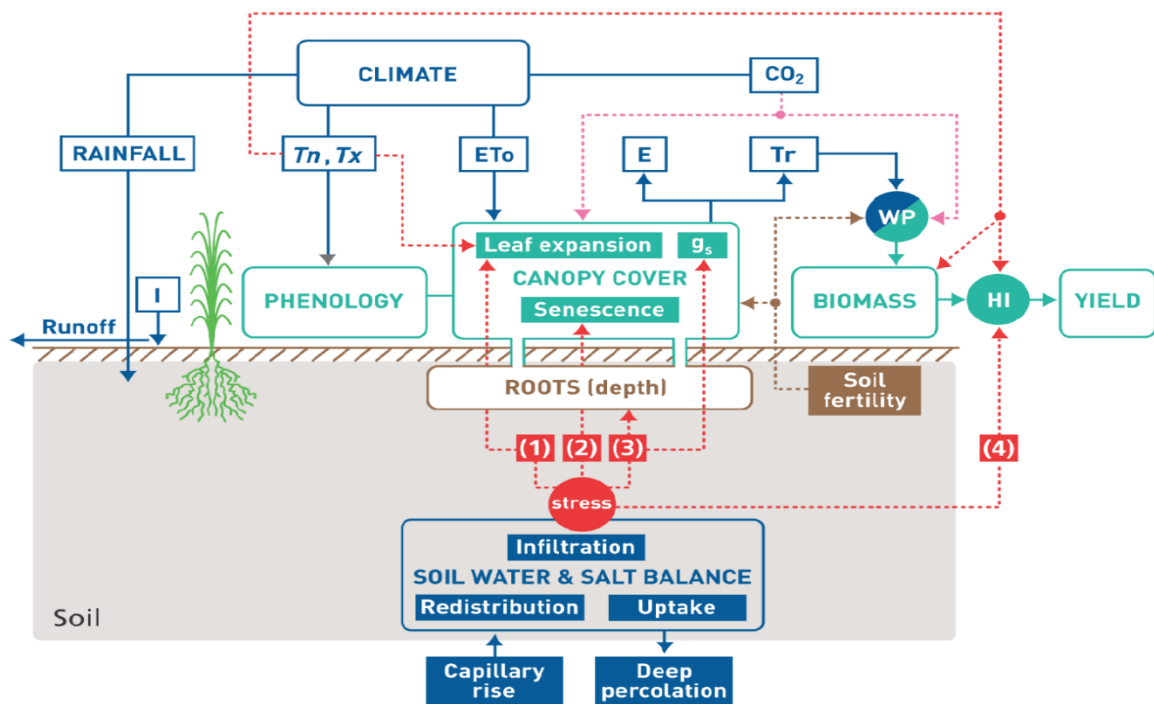


Figure 2.1: Schematic diagram of the AquaCrop engine (source Steduto *et al.*, 2012)

Steduto *et al.* (2012) recommended that the following crop parameters should be adjusted for each cultivar to reflect local conditions:

- planting date,
- planting density,
- maximum canopy cover (varies with plant density and cultivar),
- maximum rooting depth (Z_{rMAX}),
- the time required to reach Z_{rMAX} ,
- response to soil fertility,

- time to flowering or the start of yield formation,
- length of the flowering stage,
- time to start of canopy senescence, and
- time to maturity (i.e. the length of crop cycle).

AquaCrop can be used to identify best management practices that promote high crop yields, thus improving water use efficiency in rainfed conditions (Nyakudya and Stroosnijder, 2014). In the model, yield is calculated as the product of accumulated biomass production and the harvest index. The water productivity concept is fundamental and represents the relationship between biomass production and accumulated transpiration, rather than yield determination via crop evapotranspiration (Steduto *et al.*, 2009). By separating soil water evaporation and transpiration, the effect of non-productive water losses is avoided (Nyakudya and Stroosnijder, 2014). The water productivity parameter is a conservative, crop-specific parameter that is normalized using atmospheric evaporative demand and ambient carbon dioxide concentration, which makes the model applicable to a wider range of locations and seasons. Additionally, the model relies on other conservative parameters which are widely applicable and thus, do not require local calibration (Vanuytrecht *et al.*, 2014). The model structure incorporates the following components:

- Soil water balance - the model simulates soil water content in the root zone by accounting for daily incoming and outgoing water fluxes (Saab *et al.*, 2015). When the soil water content drops below a certain threshold value, the model responds by adjusting root zone expansion, canopy expansion, early senescence, transpiration and the harvest index (Van Gaelen *et al.*, 2015).
- Crop growth and development - crop growth and development is simulated over a wide range of environmental and management conditions based on climatic data, soil physical conditions, crop characteristics, irrigation and field management conditions (Van Gaelen *et al.*, 2015). Crop phenology is simulated in terms of accumulating biomass in daily time steps (Vanuytrecht *et al.*, 2014). Above ground biomass is simulated as a function of canopy expansion (CC₀), maximum canopy expansion (CC_x), canopy senescence and the time taken to reach each stage. Biomass accumulation below the ground is a function of the water extraction pattern and the maximum rooting depth. In the absence of water stress, transpiration is proportional to canopy expansion (Steduto *et al.*, 2009). Water stress is expressed through stress

coefficients related to leaf expansion, stomatal closure, canopy senescence and change in the harvest index (Voloudakis *et al.*, 2015).

- Atmospheric conditions - the model requires minimum and maximum air temperatures, rainfall and reference crop evapotranspiration. Temperature data is used to calculate growing degree days which determine crop development and phenology and accounts for biomass adjustments in cold weather (Van Gaelen *et al.*, 2015). The mean annual carbon dioxide concentrations measured at Mauna Loa in Hawaii are stored in the model (Raes *et al.*, 2009).
- Field management practices are described in more detail below.

There are two main categories of management practices in the model, namely field and irrigation management. The field management category accounts for the effects of 1) soil fertility levels and 2) mulching on crop growth. For model simplicity, soil fertility is assumed to affect canopy development and water productivity (Vanuytrecht *et al.*, 2014). The user can specify the soil fertility level as non-limiting up to severely limiting (Van Gaelen *et al.*, 2015). Adaptations of soil fertility stress on canopy development are made by 1) reducing canopy expansion, which slows canopy development, 2) reducing CC_x which results in a less dense canopy and 3) declining canopy cover once CC_x is reached at mid-season. Under mulching, the user can specify the degree of soil cover and whether the mulch residue is plant or plastic material (Raes *et al.*, 2009). The effect of mulch is simulated by reducing soil water evaporation. Under irrigation management, the user can specify whether the crop is rainfed or irrigated (Raes *et al.*, 2009). The AquaCrop model has been reported to perform well under slight to moderate water stress, compared to severe water stress conditions (Heng *et al.*, 2009; Todorovic *et al.*, 2009). The AquaCrop model has been used to simulate the water use efficiency of soybean at varying spatial scales, ranging from local scale, such as in the study carried out by Moyo and Savage (2014) in Baynesfield. The model was also used to estimate soybean water use in South Africa by Kunz *et al.* (2015). Furthermore, AquaCrop was applied in the North China Plain by Paredes *et al.* (2015).

2.4.2 The SWB model

The soil water balance model (referred to as SWB model hereafter) is a user-friendly, generic crop growth and irrigation scheduling model (Annandale *et al.*, 2000) and Jovanovic and Annandale (2000). The model can be run using either the mechanistic crop growth model or the FAO-type crop factor model. The crop growth model estimates crop growth and the soil

water balance while the FAO-type crop factor model estimates the soil water balance without physically simulating dry matter accumulation and canopy development. In this study, the mechanistic crop growth model was deemed appropriate and used for the estimation of the soil water balance. A detailed description of the model is given by Annandale *et al.* (2000). Briefly, the model uses soil, crop, weather and management data to simulate the soil water balance (Jovanovic and Annandale, 2000).

The soil layer is divided up into eleven units, each with its' own physical characteristics pertaining to soil depth. The simulated leaf area is used to calculate canopy radiant interception from which potential evapotranspiration is divided into potential evaporation and potential transpiration. Soil evaporation is assumed to occur only in the topsoil layer. A cascading soil water balance is calculated after losses of canopy interception and runoff have been accounted for (Jovanovic and Annandale, 2000). The SWB model requires inputs of rainfall and irrigation amounts. Runoff is calculated using the curve number method. Soil water redistribution is simulated by filling up each soil layer to saturation from the top to the bottom layer. Transpiration is accumulated on days in which root depth and fractional interception of radiation of photosynthetically active leaves are greater than zero (Annandale *et al.*, 1999). Finally, drainage is assumed to occur when the soil water content of the soil layer exceeds field capacity but also accounting for the soil specific parameter, namely the drainage factor.

Dry matter is accumulated in daily increments as being either water (i.e. transpiration after adjustment for vapour pressure deficit) or radiation limited, depending on the most limiting resource (Fessehazion *et al.*, 2014). The calculated dry matter accumulation is then partitioned to roots, stems, leaves and grain (Annandale *et al.*, 1999). Crop phenology and yield are estimated as a function of soil water availability (i.e. water stress) and environmental conditions (i.e. thermal time) (Fessehazion *et al.*, 2014). Factors that are not accounted for in the model (e.g. insects and herbicides) may result in poor model simulations since predicted yields may be higher than the observed values (Jovanovic and Annandale, 2000). However, the model allows for yield gap analysis to be undertaken.

Model input requirements include planting date, longitude, latitude, rainfall and irrigation amounts, daily minimum and maximum air temperatures, soil depth, initial soil water content, field capacity and permanent wilting point. Soil fertility levels cannot be varied as the model does not account for various soil fertility levels. Another limitation of the model is that it does

not account for the effects of the mulch residue. The specific input parameters used in this study are presented in **Section 3.9.2**.

2.5 Summary

This study was guided by the specifications of the National Biofuel Industrial Strategy (NBIS, 2007), which seeks to include smallholder farmers in the biofuel value chain. Due to food security concerns, the Biofuel Regulatory Framework (DoE, 2014) does not support the production of biofuel feedstock on currently productive commercial farmlands. Instead, smallholder farmers residing on under-utilized land are favoured. Furthermore, irrigation of the feedstock requires detailed motivation. Hence rainfed, production of the feedstock is favoured.

However, smallholder farmers experience low crop yields. According to literature, the main contributing factors are low soil water availability (due to low and erratic rainfall), poor soil fertility and poor weed management. The aim of this study was therefore to investigate the impacts of soil water availability (improved by mulching) and soil fertilization (application of fertilizer) on crop yield and water use efficiency. The selection of soybean was made based on the crop being identified as a strategic feedstock in the Biofuel Regulatory Framework (DoE, 2014). Biofuel manufacturers also proposed to produce a total on 480 ML of biodiesel from soybean. A field trial was conducted to help achieve the important aim of the study, namely the parameterization of the AquaCrop model. The SWB model was then used to compare simulations of crop water use and yield made by AquaCrop. Model evaluation was based on observed field data.

3 MATERIALS AND METHODS

This chapter describes the approach taken in this study to achieve the main aim, which is to estimate water use, crop yield and finally, water use efficiency of soybean in rainfed conditions using the AquaCrop model. This section details the location (*cf.* **Section 3.1**) and design of the soybean trial (*cf.* **Section 3.2**), installation of field equipment (*cf.* **Section 3.3**) as well as data collection and monitoring methods pertaining to the climate, soil and the crop (*cf.* **Section 3.5**). Finally, the field trial is linked to the modelling component, after which the statistical indicators used in the study are listed and described (*cf.* **Section 3.8**).

3.1 Trial Location

A field trial was conducted at Swayimane High School (29°31'08.02''S; 30°41'35.59''E; 883 m a.s.l.) in KwaZulu-Natal, South Africa (**Figure 3.1**). The school environment is fenced, which helped protect the trial against equipment theft and animal damage, e.g. cows.



Figure 3.1: A satellite-derived image from Google Earth® (dated 15th March 2016) showing the location of the soybean trial within the Swayimane High School

The area is located in the bioresource group called the moist midlands mistbelt, which is characterized by a mean annual temperature of 17 °C (Smith, 2006). According to the Bruyns Hill weather station the temperature ranges between 11.8 °C and 24.0 °C, which averages 17.9

°C (estimated from 1 January 1998 to 14 August 2016). The climate in Swayimane is hot, with relatively wet summers and cool, dry winters. The annual rainfall for Swayimane varies between 600 - 1 100 mm and the area is characterized by fertile clay loam soils. The region is a well-known for sugarcane and timber plantations, with about 75% of the villagers being actively involved in small-scale farming (Smith, 2006).

3.2 Experimental Design

The experimental design was a split-plot arranged in randomized complete blocks, with sub-plots replicated three times (**Figure 3.2**). The main factor was allocated to mulching (i.e. mulching vs. no mulching). The sub-plots comprised of fertilizer treatments which were designed to represent 0%, 50% and 100% of the recommended fertilizer amounts. The total trial area was 451 m² (or 0.0451 ha).

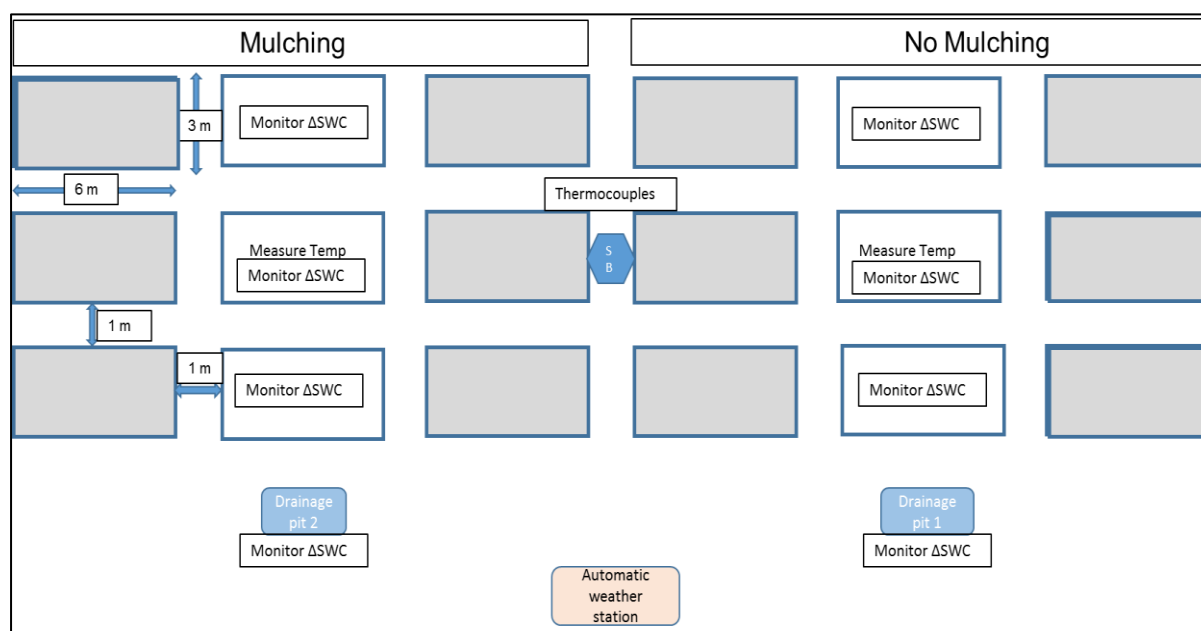


Figure 3.2: Diagram illustrating the experimental design to investigate the effects of mulching and fertilisation on water use and yield of soybean at Swayimane

Ideally, monitoring of changes in soil water content (Δ S) and soil surface temperature should take place in all plots but due to budget constraints, only certain plots were used to obtain measurements (*cf.* **Figure 3.2**). The plots highlighted in grey were left out due to boarder effects that may affect the accuracy of results. Due to the slope of the trial area, it was deemed more appropriate to locate the drainage pits at the bottom of the slope, where both lateral and vertical

water movement was highest. Furthermore, there was insufficient budget and data logger channels to place additional Watermark sensors below each of the six sub-plots as well as soil temperature sensors. The surface of the drainage pits was kept vegetation and weed free.

3.3 Equipment Installation

This section details the installation of an automatic weather station for the measurement of climatic variables at the study site (*cf.* **Section 3.3.1**). The climatic variables are required as an input into the AquaCrop and SWB models. Furthermore, the installation and data acquisition from soil Watermark sensors and thermocouples is detailed (*cf.* **Section 3.3.2**). A summary of the depths at which different field measurements were obtained is presented in **Table 3.1**.

3.3.1 Automatic weather station

An automatic weather station (AWS) was installed at the Swayimane site (**Figure 3.3**). The AWS consisted of the following sensors supplied by Campbell Scientific Africa (Somerset West, RSA):

- HMP 50 Temp/RH sensor which measures air temperature and relative humidity,
- RM Young 03101 wind speed sensor,
- LI200S pyranometer to measure solar radiation, and
- Texas Electronics TE525 (WS) rain gauge, where each tip represents 0.254 mm of rainfall.

The following sensors were installed approximately 2 m above the ground: solar radiation, air temperature, relative humidity and wind speed. The sensors were connected to a CR800 data logger (Campbell Scientific Africa, Somerset West, RSA).



Figure 3.3: Automatic weather station set up at Swayimane

The AWS was powered by two 12V DC batteries connected in parallel to maximise the time interval between battery recharging. Measurements were recorded in 15-minute intervals, then averaged to hourly and then daily values. From the AWS, the following daily weather parameters were obtained:

- maximum (T_{MAX}) and minimum (T_{MIN}) air temperature ($^{\circ}C$),
- maximum (RH_{MAX}) and minimum (RH_{MIN}) relative humidity (%),
- solar radiation (R_s in $MJ\ m^{-2}$),
- wind speed (u_2 in $m\ s^{-1}$),
- rainfall (mm) and
- reference crop evapotranspiration (ET_0 in mm).

3.3.2 *Soil water tension*

As shown in **Figure 3.2**, the middle rows were used for monitoring ΔS using soil Watermark sensors (Irrometer, Riverside CA, USA) at depths of 0.15, 0.30 and 0.60 m as well as soil surface temperature in one mulched and non-mulched plot. The Watermark sensors were connected to PVC conduit to assist installation using an auger. Once a hole was dug, the wet (previously soaked in water) sensor was dipped in soil and water slurry and placed in the hole, which was then back-filled with the slurry.

The Watermark sensors were connected to cable wire so that they could be placed at the desired depths and run from the installation point to the centre of the trial, where the CR1000 data logger (Campbell Scientific Africa, Somerset West, RSA) and strongbox were located. An AM16/32-channel relay multiplexer (Campbell Scientific Africa, Somerset West, RSA) was used to expand the data logger's channels from 8 to 32. The system was also powered by two 12V DC 12 Ah batteries connected in parallel (to increase the time between battery charging). The battery voltage was monitored weekly and batteries were changed once the voltage dropped below 12.2V DC. Thermocouples were placed near the strongbox at depths of 0.20, 0.40, 0.60, 0.80 and 1.0 m. This allowed for the correction of Watermark sensor measurements for temperature differences (where the Watermark sensors at 0.15 and 0.30 m depths in the field were represented by the thermocouples at 0.20 and 0.40 m, respectively).

Additional Watermark sensors were installed in the drainage pits (at depths of 0.20, 0.40, 0.60, 0.80 and 1.0 m) to observe vertical water movement within the soil profile, i.e. the movement of the wetting front (*cf.* **Table 3.1**). However, due to time constraints, data was acquired from drainage pit 1 only. Therefore, drainage pit 1 measurements were used for subsequent analyses. In this case, no PVC conduit was used since the pits were manually dug allowing for direct sensor placement at the different depths. In addition, disturbed soil samples for gravimetric analysis were taken (*cf.* **Figure 3.2**) at five depths (0.2, 0.4, 0.6, 0.8 and 1.0 m) using an auger.

Table 3.1: Summary of soil depths at which different measurements were obtained

Wetting front depth (m)	In-field depth (m)	Gravimetric sample depth (m)	Soil temperature depth (m)	Soil water retention characteristics depth (m)
0.2	0.15	0.2	0.2	0.15
0.4	0.3	0.4	0.4	0.3
0.6	0.6	0.6	0.6	0.6
0.8	-	0.8	0.8	0.9
1.0	-	1.0	1.0	-

Note: - indicates values that were not obtained

Furthermore, undisturbed soil samples for the determination of soil water retention characteristics were obtained before the drainage pit was closed. The soil core samples were placed in re-sealable plastic bags to ensure no moisture was lost during transport to the soils laboratory for analysis. The strongbox in the centre of the trial housed all the Watermark sensors cables and thermocouples to a data logger where data was recorded at time intervals of

15 minutes, hourly and daily. Field visits were done regularly to download data and take crop growth measurements.

3.4 Agronomic Practices

A description of site preparation that was undertaken and details of planting is detailed below. Furthermore, details of the execution of the treatments under study in the field in order to investigate the effects of mulching and soil fertility on crop water use and yield are discussed.

3.4.1 *Site preparation*

As noted earlier, the agronomic practices that were considered in this study included mulching and fertilization. Land preparation was done before planting by ploughing and disking. Hand-hoes were then used to achieve a smooth tilth for planting. Land preparation and weeding were done manually by some members of the community at a set fee. Hence, the Swayimane trial provided a source of income for the local community.

3.4.2 *Planting*

According to DAFF (2010a), an inter-row spacing of 0.4-0.9 m and intra-row spacing of 0.05-0.15 m is recommended in order to achieve a planting density of 250 000-400 000 plants ha⁻¹. Soybean cultivar LS6161R was planted with an inter-row spacing of 0.75 m and an intra-row spacing of 0.05 m. After planting, the trial was thinned in some parts and gap filled in others in order to achieve the targeted plant density of 266 667 plants ha⁻¹.

3.4.3 *Fertilization*

Soil samples from the top 0.15 m across the field were taken before planting for soil fertility analysis. The analysis was undertaken by the Soil Analytical Service Laboratory, based at the Cedara College of Agriculture, using recognised techniques as described by Manson and Roberts (2000). The recommended fertilizer application rate was 0 kg ha⁻¹: 60 kg ha⁻¹: 95 kg ha⁻¹. This rate was adjusted accordingly for the 50% fertilizer level, while no fertilizer was applied in the 0% fertilizer level. Based on soil fertility results, single superphosphate, namely P (10.5%) and KCl (0-0-60) were used to fertilize the trial. Fertilizer was added before planting by broadcasting. Insecticide was applied twice after emergence as insect occurrence had been noticed.

3.4.4 *Mulching*

Hay bales were used for mulch, which consisted of natural grassland obtained from the University of KwaZulu-Natal's Research Farm (Ukulunga). Each hay bale weighed approximately 25 kg. Ten hay bales were used throughout the growing season (i.e. 250 kg of straw mulch in total). Additional mulch was added when the ground cover became sparse due to decaying mulch. The mulch was applied to half of the sub-plots (i.e. 9 of 18 in total; cf. **Figure 3.4**), which represented a mulched area of 0.0226 ha (approximately 11 000 kg ha⁻¹). The application of mulch was such that a uniform amount was placed over to ensure that the ground was well covered and the thickness was measured at 5 cm for the mulch layer. The mulch was applied after emergence to prevent the mulch layer from negatively impacting the establishment of the crop.



Figure 3.4: Mulch residue applied over half of the treatments in the Swayimane trial

3.5 Data Collection and Monitoring

Data collection was designed to meet the requirements for calibrating and validating the AquaCrop model. The model requires daily weather (rainfall, temperature and reference crop evapotranspiration), soil (texture, depth and water retention properties) and crop development data (planting date, planting density, maximum rooting depth, response to soil fertility and the length of certain phenological growth stages) in order to provide estimates of attainable crop yield and water use. Regular site visits were made to obtain the necessary measurements.

3.5.1 Climatic data

Daily weather data was derived from hourly measurements and used to develop a climate file (of T_{MAX} , T_{MIN} , rainfall and ET_O) as required by the AquaCrop model. Soybean seed was planted on the 6th of November 2015 and harvested on the 29th of March 2016. However, the weather station only started recording data on the 16th of December 2015 due to unavailability of technical staff to assist with the installation. The derivation of ET_O is described next.

3.5.2 Reference crop evapotranspiration

The FAO Penman-Monteith equation was used to estimate reference crop evapotranspiration for a hypothetical surface representing a well-watered, short grass surface (with fixed surface resistance of 70 s m^{-1}) of uniform height (0.12 m) that is actively growing (albedo of 0.23) and completely shades the ground (Allen *et al.*, 1998).

The data logger calculated daily ET_O at the time of measurement of weather data. However, calculated values were unrealistically low due an error in the summation of hourly to daily values of solar radiation. Hence, ET_O values were computed using FAO's ET_O Calculator utility, which was obtained from the Internet (<http://www.fao.org/nr/water/eto.html>). According to FAO (2012), the ET_O Calculator can estimate reference crop evapotranspiration in daily, ten-day or monthly time steps according to FAO standards, as described by Allen *et al.* (1998). The specified climatic data, including the estimated ET_O data can be conveniently exported to text files using the utility.

3.5.3 Plant material

Soybean cultivar LS6161R was donated by Link Seeds during October 2015. LS6161R is a Roundup® Ready, medium growth class (semi-determinate growth type), narrow-leaf cultivar that is well adapted to both dryland and irrigated growing conditions. The cultivar reaches 50% flowering in 60 to 68 days, and takes 140 to 150 days to reach harvest maturity with plant height varying between 95 and 105 cm (Link Seeds, 2011).

A Roundup® Ready soybean cultivar was selected to allow comparison with research conducted at Baynesfield Estate (situated 25 km south of Pietermaritzburg). However, smallholder farmers cannot afford Roundup® Ready cultivars. It is cheaper to inoculate soybean than use a Roundup® ready cultivar, especially for smallholder farmers. In general, legumes such as soybeans do not require nitrogen fertilizer as they can fix atmospheric nitrogen

through a symbiotic relationship with *Bradyrhizobium japonicum* bacteria. However, in cases of low *Bradyrhizobium japonicum* bacteria population in the soil, the seed should be inoculated. Unfortunately, smallholder farmers do not opt for this option because they fail to grasp the concept of biological nitrogen fixation. Furthermore, they do not know where the inoculants may be acquired (van Vugt *et al.*, 2016). Inoculation was therefore excluded to make this study as representative of smallholder farming conditions as possible.

3.5.4 Soil characterisation

Soil is a porous medium, consisting of solids, liquids and gases (Vermaak, 2000). An understanding of these relations is necessary to better understand the interaction between the soil, plant and atmosphere continuum. Soil water measurements are important for monitoring water extraction and availability within the root zone (Stevens, 2007). The status of soil water can be determined directly by i) measuring soil water content, or ii) indirectly by measuring water retention through soil water potential. The difference between measuring soil water potential and soil water content is that suction can be used as an indicator of water availability to plants, whereas soil water content simply expresses a fraction of water present in the soil profile (Stevens, 2007).

Soil profiling was done at the study site by manually digging two 1 m² by 1 m deep pits. These also served as the drainage pits after the soil profiling was completed. The analysis of soil characteristics was essential in order to characterize the relevant soil properties. The study focused on soil properties that influence soil water fluxes such as soil texture, dry bulk density (ρ), total porosity (TPO), saturation (SAT), field capacity (FC), permanent wilting point (PWP) and total available water (TAW) as well as saturated hydraulic conductivity (K_{SAT}). These soil properties, including soil profile depth, are required as input by the AquaCrop model. Disturbed soil samples were obtained from drainage pit 1 for the analysis of soil texture. Undisturbed soil samples were also obtained from drainage pit 1 using soil cores in order to determine the dry bulk density, as well as soil water retention at porosity and field capacity.

3.5.4.1 Soil texture

The USDA classification system was adopted by South Africa's taxonomic soil classification system (SCWG, 1991) and is also used by the AquaCrop model. An analysis of soil texture was undertaken at five different depths, namely, 0.2, 0.4, 0.6, 0.8 and 1.0 m (see **Appendix 2** for results). This analysis was undertaken by the Soil Analytical Service Laboratory, based at

the Cedara College of Agriculture, using recognised techniques as described by Manson and Roberts (2000).

3.5.4.2 Dry bulk density

The dry bulk density represents the mass of dry soil (mass of solids) per unit volume of soil (White, 2003). Bulk density values typically range from 1.1 to 1.6 g cm⁻³ for fine textured soils (Hillel, 1998). A low bulk density implies a favourable soil structure for root penetration as it is not compacted (Karuku *et al.*, 2012). For dry bulk density, a soil core containing an undisturbed sample was placed in the oven for 24 hours at 105 °C to dry, an oven temperature used by several authors including Gebregiorgis (2003) and Mhizha *et al.* (2014). The length and diameter of the soil core was measured and dry bulk density was calculated as the mass of solids divided by the volume of soil in the metal core.

However, low bulk density values were measured in the top 0.3 m soil depth. This was due to the acquisition of soil samples after the land preparation (by ploughing). The measured value was 1.08 g cm⁻³ while the controlled outflow method estimated a value of 1.36 g cm⁻³ which was comparable with the SPAW estimate of 1.38 g cm⁻³ (*cf.* **Table 4.2** and **Table 4.3**, respectively in **Section 4.2** for results). Therefore, the bulk density values estimated from the controlled outflow method were used in this study and not the measured values.

3.5.4.3 Soil water content

Soil water content can be expressed gravimetrically (i.e. by mass) or volumetrically (i.e. by volume). The gravimetric method is a simple approach to determine the mass of water present in the soil sample. Gravimetric water content was measured directly by finding the mass of water lost when a soil was dried in an oven at 105 °C for 24 hours (Marshall and Holmes, 1988; Stevens, 2007). A disadvantage of the method is that some organic matter may oxidize at this temperature and thus, loss of mass is not solely due to the evaporation of soil water (Hillel, 1998). The gravimetric water content (θ_g in g g⁻¹), is expressed as the difference between wet and dry mass divided by dry mass.

Volumetric water content (θ_v) is usually preferred over gravimetric water content as it expresses the volume of water per volume of soil (White, 2003). Gravimetric content was converted to volumetric content by dividing the product of gravimetric water content and dry bulk density with the density of water. This method was used in this study to calibrate the soil Watermark sensor readings. Using a soil auger, seven disturbed gravimetric samples were obtained at five depths (0.2, 0.4, 0.6, 0.8 and 1.0 m) from drainage pit 1 over the growing season. However, at

the beginning of the season, gravimetric samples were acquired from the top 0.6 m soil depth, hence the 0.8 m and 1.0 m soil depths are missing a single measurement (*cf.* **Appendix 8**).

3.5.4.4 Soil water retention parameters

Four undisturbed soil samples were taken from drainage pit 1 at four depths (0.15, 0.3, 0.6, 0.9 m) in order to determine the soil's total porosity (or saturation) and field capacity (or drained upper limit) values. These two soil water parameters were obtained using the controlled outflow method in the soils laboratory at UKZN, as described in more detail in **Appendix 3**. Briefly, each soil sample was initially saturated with water, then desorbed by applying increasing pressure to the drying sample, while taking successive measurements of the corresponding water loss (Adhanom *et al.*, 2012). The suction pressure applied to each soil core ranged from 0 to -100 kPa. The water released from the sample at 0 kPa represents θ_{TPO} , i.e. the maximum water content of the soil when almost all pores are replaced by liquid water (Vermaak, 2000). Similarly, θ_{FC} describes the water content held within the soil after natural drainage has occurred (i.e. against the force of gravity), which is assumed to occur at a suction force of -33 kPa, in accordance with most available literature. According to Gebregiorgis and Savage (2006), field capacity is defined as the soil water content at which drainage from pre-wetted soil ceases or the rate of decrease is ± 0.001 to $0.003 \text{ m}^3 \text{ m}^{-3}$ per day.

3.5.4.5 Estimation of permanent wilting point

The permanent wilting point (θ_{PWP}) is the soil water content at which the crop begins to permanently wilt due to water stress and is assumed to occur at a suction force of -1500 kPa. Permanent wilting point can be only measured using high pressure plates, which can withstand an applied pressure up to 15 bar (-1500 kPa). However, due to the unfortunate failure of the high-pressure air compressor in the soils laboratory at UKZN, the permanent wilting point could not be measured. Hence, θ_{PWP} was estimated with the soil water characteristics calculator (SPAW) as updated by Saxton and Rawls (2006) from the Saxton *et al.* (1986) equations using soil texture. The model was obtained from the Internet (<https://hrs1.ba.ars.usda.gov/soilwater/Index.htm>). The SPAW estimates were compared to those made by RETention Curve (RETC) PC-based utility (van Genuchten *et al.*, 1991).

The input parameters for the SPAW model (*cf.* **Table 3.2**) were the relative soil fractions (*cf.* **Appendix 2**) and organic matter content of the topsoil (%), which was calculated by multiplying the organic carbon (*cf.* **Table 4.6** in **Section 4.5.1**), as measured by the Soil Analytical Service Laboratory, by a factor of 1.724 (Howard, 1965). Soil organic matter was

set at default values for the specified soil texture classes at other depths as soil organic matter was not determined at these depths due to budget limitations. The 0.8 and 1.0 m depths were averaged to give texture estimates for the 0.9 m depth. Similarly, samples taken at 0.2 and 0.4 m were used to represent the soil at 0.15 and 0.3 m respectively. Furthermore, compaction at the two lowest depths were reduced in order to account for the lower bulk densities at these depths. Soil salinity and gravel were not considered in this study and were therefore left at default values of zero.

Table 3.2: Input parameters used in the SPAW model

Soil depth (m)	Sand (%)	Clay (%)	Organic matter (%)	Compaction
0.15	49	36	5.2	1
0.3	48	41	-	1
0.6	46	47	-	0.95
0.9	39	55	-	0.95

The RETC program is commonly used to estimate soil hydraulic properties by simulating the soil water retention curve from measured data (Kanzari *et al.*, 2012). A detailed description of RETC was reported by van Genuchten *et al.* (1991). The RETC uses a non-linear least square optimization approach to estimate unknown parameters from measured soil water retention data (van Genuchten *et al.*, 1991). The RETC provides parameters required in the van Genuchten (1980) equation to calculate volumetric soil water content ($\text{cm}^3 \text{cm}^{-3}$) from the hydraulic head of water (cm).

The RETC program was used to access the built-in ROSETTA Lite v1.1 software, from which the van Genuchten (1980) parameters were predicted, based on the relative soil fractions (*cf.* **Appendix 2**), the water content at field capacity (*cf.* **Table 4.3**) and bulk density (*cf.* **Table 4.3**). Furthermore, the final pressure and water content, which were estimated using the controlled outflow method (*cf.* **Appendix 7**), were added as input into the RETC model in order to provide an estimate of the permanent wilting point. The Mualem conductivity model in RETC was selected for this step.

3.5.4.6 Total available water

Total available water (TAW) represents the soil water between θ_{FC} and θ_{PWP} that is available for plant uptake (Tan, 1996; Stevens, 2007). This parameter is also referred to as plant available water or PAW, i.e. $\text{PAW} = \theta_{FC} - \theta_{PWP} = \text{TAW}$.

3.5.4.7 Soil water retention curve

The soil water retention curve represents the relationship between soil water content and soil water potential (White, 2003; Shweta and Varija, 2015) and is an accurate characterization of soil pore structure (Lorentz *et al.*, 2004). A higher clay content results in greater water retention and a more gradual slope of the curve. Similarly, the higher the sand fraction, the less water is retained by the soil (Gebregiorgis, 2003). Therefore, the soil water retention curve is strongly affected by soil texture. For this study, the RETC program (*cf.* **Section 3.5.4.5**) was used to extrapolate the measured soil water retention curve (from 0 to -100 kPa) to the soil's permanent wilting point (i.e. -1500 kPa). This method provided similar field capacity and permanent wilting point values to those from the SPAW model. However, SPAW estimates were deemed more appropriate and thus, selected for use in this study (*cf.* **Table 4.3** in **Section 4.2.4** for results).

3.5.4.8 Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_{SAT}) represents the ease of water flow when a soil is saturated and is subjected to a hydraulic gradient. Saturated hydraulic conductivity typically decreases with increasing soil depth due to the presence of less organic matter and increasing clay content (Karuku *et al.*, 2012). Saturated hydraulic conductivity can be measured in the laboratory using the constant head method (Hillel, 1998) or *in-situ* using the double ring infiltrometer (Reynolds *et al.*, 2002) and Guelph permeameter method (Reynolds, 1993). The *in-situ* measurements are preferred over laboratory measurements since they provide more realistic (i.e. undisturbed) field conditions. Furthermore, the constant head method is more time consuming than *in-situ* measurements (Shweta and Varija, 2015). However, due to the difficulty in obtaining measurements, K_{SAT} was estimated by SPAW in this study.

3.6 Actual Crop Evapotranspiration

Soil water evaporation (E) is the transfer of water vapour from the soil to the atmosphere, whereas transpiration (T) is the transfer of water vapour from the plant into the atmosphere. The total water lost through these processes is commonly known as evapotranspiration (ET). According to Allen *et al.* (1998), the factors that affect ET are:

- weather conditions such as solar radiation, air temperature, humidity and wind speed,
- crop factors such as crop type, cultivar and developmental stages,
- management conditions, and

- soil water availability.

The AquaCrop and SWB models were used to estimate crop evapotranspiration (*cf.* **Section 4.7** for results). However, the SWB model simulated WUE under the full fertilizer, non-mulched treatment only, because it cannot account for mulching and varying soil fertility levels. On the contrary, AquaCrop was used to simulate WUE under all treatments under study. Both model simulations were then compared to observed field data (e.g. leaf area index, biomass accumulation, final yield and biomass and profile water content) to determine model accuracy. Furthermore, a close correlation of simulations made by both models would improve confidence in simulations made by AquaCrop for all treatments under study. The estimation of profile water content under field conditions is described next, followed by a brief discussion on crop coefficients.

The soil water balance equation can be used to quantify ET, given that all other components are known. The soil water balance equation to calculate actual crop evapotranspiration (ET in mm) is expressed as:

$$ET = P + I - D - I_R - I_C - R \pm \Delta S \quad \text{Equation 3.1}$$

The above equation accounts for gains such as precipitation (P) and irrigation (I), as well as losses through drainage (D), residue or litter layer interception (I_R), canopy interception (I_C) and runoff (R) as well as changes in soil water content (ΔS). The soil water balance method can provide dependable estimates of crop ET, provided that the fundamental factors pertaining to vegetation and environmental conditions are well represented (Allen *et al.*, 2011). The soil water balance equation could not be used to estimate crop water use in the field since runoff was not measured and could not be assumed to be negligible. However, measurements of rainfall were used to parameterize both AquaCrop and the SWB models. Interception is not accounted for by the AquaCrop model, but was assumed to equal 1 mm per rain event in the SWB model, which is the model's default value for soybean (Annandale *et al.*, 1999). Drainage was estimated by accumulating excess soil water above field capacity in each soil layer. Change in soil water content was monitored using Watermark sensors as described next

3.6.1 Profile water content

Watermark sensors (model A200SS-5, Irrometer, Riverside CA, USA) were used to measure the electrical resistance that changes with the presence of water in the soil (Stevens, 2007). A

loss of water results in an increase in resistance measured by the sensor (Irrometer, 2015). Before installation, the sensors were subjected to two cycles of soaking in water for an hour and dried for two days, as recommended by Campbell Scientific Inc. (CSI, 2013). The sensors were then saturated again at least 30 minutes before installation and measurements of water potential were taken to ensure functionality. All sensors gave readings between 0 to 5 kPa, which implied full functionality (CSI, 2013). However, the Watermark sensor at the 0.15 m depth in the mulched, half fertilizer treatment plot occasionally recorded unrealistic values. For this reason, the Watermark sensor was excluded in all calculations. The installation of Watermark sensors was done in locations with representative soil and crop conditions, as recommended by Irmak *et al.* (2016).

Watermark sensors are easily installed, require minimal maintenance and can monitor soil water potential at multiple depths (Stevens, 2007). Additionally, they are relatively inexpensive and accurate compared to other sensors. Limitations of the Watermark sensors include sensitivity to temperature and susceptibility to inaccuracies that are caused by soil disturbance during installation (Chard, 2002). The temperature adjustment of Watermark sensor readings was undertaken in this study using the method (*cf.* **Equation 7.7** in **Appendix 4**) described by Allen (2000). Other methods that were evaluated are further described in **Appendix 4**.

Varble and Chávez (2011) found that field-derived logarithmic and van Genuchten (1980) equations were equally accurate calibrations of Watermark sensors for estimating volumetric water content from readings of soil matric potential. A similar approach to that used by Varble and Chávez (2011) was adopted in this study. A flow chart summarizing both methods is shown in **Figure 3.5**.

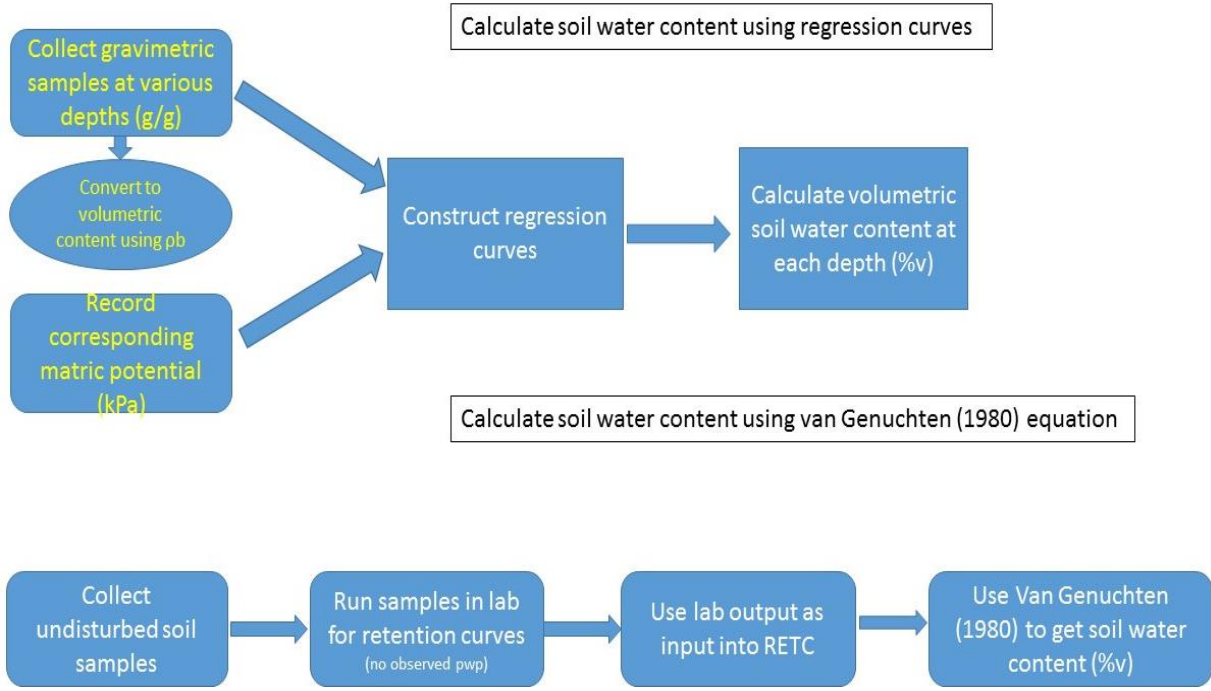


Figure 3.5: A schematic flow chart of approaches followed to convert soil matric potential (kPa) to volumetric water content (%v)

For the calibration of Watermark sensors, undisturbed soil core samples were taken at the depth of sensor installation. Once in the laboratory, the cores were weighed and oven dried at 105°C for 24 hours and re-weighed to calculate gravimetric water content. Volumetric water content was calculated using the soil bulk density and that of water (*cf.* **Section 3.5.4.3**).

The Watermark sensors were read at the same time as the soil samples were taken. For calibration, the volumetric water content (θ_v) determined from the soil samples were regressed against the soil water tension readings in kPa (Shock *et al.*, 2016). A logarithmic regression for each soil depth was obtained as follows:

$$\theta_v = \alpha \cdot \ln(P) + \delta \quad \text{Equation 3.2}$$

where P = soil pressure head (cm; to remove the negative from soil matric potential) and α and δ represent the slope and the intercept, respectively.

Another approach to convert soil water tension from a pressure head (P in cm) to volumetric water content (θ_v in $\text{cm}^3 \text{cm}^{-3}$) is through the van Genuchten (1980) model. Both pressure potential (kPa) and pressure head (cm) are a measure of tension, the only difference is the units. The pressure head was calculated by multiplying the pressure potential (kPa) by -10.2 so that positive values could be obtained (i.e. log of negative values is thus avoided). The van Genuchten (1980) model requires the following four water retention parameters:

- θ_R is the residual water content ($\text{cm}^3 \text{cm}^{-3}$),
- θ_S is the saturated water content ($\text{cm}^3 \text{cm}^{-3}$), and
- α ($> 0, \text{cm}^{-1}$) and n (> 1 ; dimensionless) are shape parameters.

The soil's porosity value was used to estimate θ_S . According to van Genuchten (1980), α is related to the inverse of the air entry suction and n is a measure of the pore-size distribution. The value of α is approximately the inverse value of matrix potential at the inflection point in the van Genuchten retention curve. The value of n influences the overall shape of the water retention curve. As soil texture becomes finer, α and n decrease and θ_R increases (Schaap *et al.*, 2001).

3.6.2 Crop coefficients

Crop coefficients indicate water use during various crop growth stages. The peak monthly crop coefficient indicates the month in which water use is the highest. Crop coefficients are affected by crop type, crop growth stage, climate and soil evaporation (Allen *et al.*, 1998). Seasonal crop coefficients were determined using **Equation 3.3** from estimates of actual crop evapotranspiration (ET in mm) and reference crop evapotranspiration (ET_o in mm) as follows:

$$K_c = \frac{ET}{ET_o} \quad \text{Equation 3.3}$$

3.7 Plant Growth and Yield

Destructive sampling (above-ground) was done during field visits in order to determine biomass accumulation. In addition, the occurrence of significant crop growth stages (phenology) was observed during the growing season (**Table 3.3**). For detailed descriptions of phenological stages, the reader is referred to Mabhaudhi *et al.* (2014).

Table 3.3: Key phenological events for soybean

Growth stage	Number of days after sowing to reach
Seedling emergence	90% emergence of seedlings
Flowering	floral initiation based on at least 50% of plants having flowered
Time to yield formation	50% pod formation on plants
Time to senescence	50% of the plant has turned yellow from the bottom-up, and 50% of all plants have turned yellow
Time to maturity	50% of plants have reached harvest maturity

Crop phenology was observed in calendar days and later converted to thermal time. Growing degree days (GDD) were calculated using a method similar to that described by McMaster and Wilhem (1997) as follows:

$$GDD = \left[\frac{T_{MAX} + T_{MIN}}{2} \right] - T_{BSE} \quad \text{Equation 3.4}$$

where, GDD = growing degree days (d °C),

T_{MAX} = daily maximum air temperature (°C),

T_{MIN} = daily minimum air temperature (°C), and

T_{BSE} = base temperature (°C), which is the temperature below which crop growth ceases.

Data collection also included plant growth parameters such as leaf area index (using an LAI-2200, Li-Cor Inc., USA) and stomatal conductance (via a Leaf Porometer, Model SC-1, Decagon Devices, USA). Diffuse non-intercepted radiation (DIFN), an output of the LAI-2200 canopy analyser, was used to calculate canopy cover (CC), which is a measure of the above-ground biomass, based on the following equation by Mabhaudhi *et al.* (2014):

$$CC(\%) = 1 - DIFN \quad \text{Equation 3.5}$$

Biomass accumulation (or total dry matter) was estimated by measuring the weight of a representative plant (with the roots removed prior to weighing), which was acquired in the field through destructive sampling.

3.7.1 Seed yield and harvest index

Plants were harvested when they reached harvest maturity. Six representative plants were harvested from each plot, from which the average final biomass (B), yield (Y) and harvest index (HI) were determined. Final biomass was estimated by measuring the total above ground biomass, including pods. Thereafter, the pods were separated from the foliage and pod yield was determined. Following this, the pods were shelled and then the seed yield was determined. The harvest index was calculated as the ratio of seed yield to final biomass:

$$HI = \frac{Y}{B} \cdot 100 \quad \text{Equation 3.6}$$

where HI = harvest index (%),

Y = seed yield (t ha^{-1}), and

B = final biomass (t ha^{-1}).

3.7.2 Seed oil content

In this study, soybean seed oil was extracted and quantified using a technique described by Meyer and Terry (2008). Briefly, 1 g of ground lyophilised seed tissue was homogenised with hexane solvent and filtered under vacuum using Fisherbrand filter paper. The solvent was evaporated from the oil-containing filtrate under vacuum. The recovered oil was weighed using a scintillation vial and the percentage calculated [% (w/w)]. The results of this analysis are presented in **Section 4.6**.

The biofuel yield can be estimated from the product of the crop yield and the extraction rate (Kunz *et al.*, 2015) or the theoretical biofuel yield equation, which is expressed as:

$$\begin{aligned} \text{Biodiesel yield (L ha}^{-1}\text{)} &= \text{seed oil content (\%)} \cdot \text{Equation 3.7} \\ &\text{dry seed yield (t ha}^{-1}\text{)} \cdot \\ &10 \cdot 0.95/0.92 \end{aligned}$$

The theoretical biofuel yield equation is recommended because it takes into account both the crop yield and the seed oil content. The equation is based on the following assumptions:

- all bio-oil can be extracted from the seed,
- the conversion efficiency is 95% (Nolte, 2007), and
- an oil density of 0.92 kg L^{-1} , which is typical for soybean (Atabani *et al.*, 2013).

3.8 Linking Field Measurements to Modelling

The objectives of the modelling component of this study were to simulate yield, water use and finally, the water use efficiency of soybean under rainfed conditions, as well as to provide an understanding of the impacts of fertilization and mulching on crop yield. AquaCrop has already been calibrated for soybean grown at Baynesfield (Moyo and Savage, 2014). The model was then “fine-tuned” using observed data from the soybean field trial at Swayimane. Output from the SWB model was then compared to that simulated by AquaCrop for the non-mulched, full fertilizer treatment. The output of both models was then compared with observed data pertaining to final biomass, yield and profile water content.

3.8.1 *AquaCrop calibration*

The impact of agronomic practices (i.e. mulching and fertilizing) on crop yield was assessed using the model. The control was the non-mulched, full fertilizer treatment. Model calibration was considered adequate when the simulated canopy cover, biomass and yield matched the observed values as closely as possible. During this process, model parameters were adjusted within acceptable limits, as described by Raes *et al.* (2012). The input datasets required by the model (climate, crop growth and phenology, field management and soils) are discussed below.

3.8.1.1 Climate data

A climate file consisting of minimum and maximum temperature (°C), reference crop evapotranspiration (mm) and rainfall (mm) was created for the Swayimane site. The above-mentioned data were recorded by an automatic weather station that was installed at Swayimane. The data set was extended with data recorded in Bruyns Hill for both models in order to acquire weather data from planting (discussed in more detail in **Section 4.1**). The default carbon dioxide (CO₂) file that is packaged with the model was used in this study.

3.8.1.2 Soil data

For each soil horizon, the model requires its depth, together with soil water retention characteristics such as saturation (SAT), field capacity (FC), permanent wilting point (PWP), total available water (TAW) and saturated hydraulic conductivity (K_{SAT}). In this study, the soil was divided into two soil horizons, namely a 0.60 m sandy clay and a 0.40 m clay (as per the soil texture results given in **Appendix 2**). The soil water retention characteristics for the 0.15, 0.30 and 0.60 m depths were averaged to represent the upper 0.60 m horizon. Measurements for the 0.9 m depth represented the lower 0.40 m horizon. SPAW estimates of field capacity, saturation, permanent wilting point and K_{SAT} were used to derive soil parameters required by the model. The initial soil water content was set at field capacity as the topsoil was wet before planting. The curve number was estimated as 75 based on the saturated hydraulic conductivity of the soil (Raes *et al.*, 2012). The soil parameters used are shown in **Table 3.4** below.

Table 3.4: Soil parameters used as input for modelling using AquaCrop

Soil Texture	Thickness m	PWP ¹	FC ² Volumetric (%)	SAT ³	K _{SAT} ⁴ (mm/day)
Sandy clay	0.6	26.0	42.5	52.8	50.8
Clay	0.4	32.9	52.0	54.2	6.1

Note: 1= permanent wilting point, 2= field capacity, 3= saturation, 4 = saturated hydraulic conductivity

3.8.1.3 Crop growth and phenology

A soybean file that was calibrated using data collected at Baynesfield (by Moyo and Savage, 2014 in the 2012/13 season) was used to represent local conditions. Thereafter, certain model parameters were “fine-tuned” using observed variables from the Swayimane trial (*cf.* **Table 3.5**). It is worth noting that final yield was done at field scale in Baynesfield, while it was undertaken on a per plant basis in Swayimane (due to the observed poor plant density when compared to Baynesfield). In order to account for this difference, six representative plants were obtained from each treatment in Swayimane. Thereafter, the final yield was scaled up to t ha⁻¹.

Table 3.5: Calibration of AquaCrop using observed data from the soybean trial at Swayimane

Parameter	Baynesfield value	Swayimane value
Planting date	15 October 2012	6 November 2015
Planting density	328 947	266 667
Base temperature, °C	5.0	5.0
Time to emergence, d °C	200	108
Max. rooting depth (Zr _{MAX}), m	2.0	0.6
Maximum canopy cover (CC _X) %	98.0	72.0
Time to canopy senescence, d °C	2200	1714
Time to maturity, d °C	2700	2189
Length of crop cycle, d °C	2700	2189
Normalized water productivity (WP*), g m ⁻²	15.0	13.0
WP* during yield formation, as % WP*	60.0	50.0
Crop transpiration (K _{CB})	1.10	1.0
Shape factor for K _S canopy expansion	3.0	Linear

In the model, the mulched layer was represented as 90% of the surface covered by an organic mulch. Soil fertility was simulated as non-limiting for the full fertilizer level. The half fertilizer level was simulated at 20% soil fertility stress (i.e. moderate fertility). The 0% fertilizer level simulated at 60% soil fertility stress (i.e. poor fertility).

3.8.2 SWB model calibration

3.8.2.1 Climate file

The climate file was created using weather data pertaining to solar radiation, minimum and maximum air temperature, minimum and maximum relative humidity, wind speed and rainfall, all of which were recorded by the weather station on site.

3.8.2.2 Soil data

The 1 m soil profile depth was divided into smaller increments to make up the eleven layers as required by the model. For example, the first 0.3 m soil depth was divided as 0.10 m and 0.20 m, and the soil data representative of the 0.3 m soil depth were input into both divided layers. The soil data was input as was done for AquaCrop (*cf.* **Table 3.4**). An additional requirement of the soil water balance is bulk density, which was averaged as 1.34 and 1.30 g cm⁻³ for the top and bottom horizons, respectively.

3.8.2.3 Crop growth and phenology

The soybean trial provided crop growth and phenology which were input into the model. For values that were not measured at the trial, values observed by Dlamini (2015) for soybean cultivar PAN 535 (which is a determinate, early to late maturing cultivar) were used (*cf.* **Section 3.5.3** for description of LS6161R used in this study). It is not ideal to parameterize the SWB model with different cultivars as this reduces the accuracy of simulations. However, not all field measurements could be collected and hence, the reliance on secondary data was inevitable due to limitations of both time and available resources. Since growing degree days are sensitive to the base temperature, the difference in time taken to the different crop stages are different because a base temperature of 5 °C was used in this study compared to 12 °C used by Dlamini (2015). Although results are not presented, using a base temperature of 12 °C provides more similar crop phenology values with those reported by Dlamini (2015). The base temperature of 5 °C was used in this study in order to allow for the comparison of results obtained in Baynesfield, where a base temperature of 5 °C was also used, which is the default value of soybean in the AquaCrop model. The base temperature used in the model is

conservative, meaning it is generally applicable to a wider range of growing conditions. In the study by Paredes *et al.* (2015), the default base temperature of 5 °C was also used. However, numerous sources in the literature use a base temperature of 10 °C for soybean (e.g. Knott, 1988 cited by Annandale *et al.*, 1999; Kumar *et al.*, 2008; Jescheke *et al.*, 2017). The model input parameters used in SWB are shown in **Table 3.6** below.

Table 3.6: Input parameters for the SWB model

Crop parameters	Dlamini (2015)	This Study
Canopy extinction coefficient for solar radiation	0.65	0.65
Dry matter to water ratio (DWR) (Pa)	5.0	5.0
Radiation use efficiency (kg MJ ⁻¹)	0.0012	0.0012
Base temperature (°C)	12	5
Optimum temperature (°C)	25	25
Cut off temperature (°C)	32	30
Emergence day degrees (d °C)	62	108
Flowering day degrees (d °C)	600	1023
Maturity day degrees (d °C)	1115	2189
Transition period (d °C)	550	900
Leaf senescence (d °C)	1012	1714
Maximum crop height (m)	0.66	1.0
Maximum root depth (m)	0.6	0.6
Stem to grain translocation	0.2	0.2
Canopy storage (mm)	1	1
Minimum leaf water potential (kPa)	-1500	-1500
Maximum transpiration (mm d ⁻¹)	9	8
Specific leaf area (m ² kg ⁻¹)	18	18
Leaf-stem partition (m ² kg ⁻¹)	1.5	1.5
Total dry matter at emergence (kg m ⁻²)	0.003	0.003
Root fraction	0.01	0.01
Root growth rate	5	5
Stress index	0.95	0.95

3.8.3 Water use efficiency

The simulated final seed yield and crop water use (crop evapotranspiration) were used to calculate water use efficiency (WUE) using the equation:

$$WUE = \frac{Y}{ET} \quad \text{Equation 3.8}$$

where WUE = water use efficiency (kg m^{-3}),

Y = seed yield (kg), and

ET = crop evapotranspiration (m^3).

3.8.4 Model evaluation

Data analysis was performed to identify any patterns within the data and the significance of interactions using GenStat® Version 17 (VSN International, UK). Treatment means were separated using Fishers' Unprotected Least Significant Difference (LSD) at the 5% level of probability (Snedecor and Cochran, 1980). The variables used to analyse the data were the canopy cover (CC), biomass, and yield. The number of independent factors which can be assigned to a statistical distribution is known as degrees of freedom (Walker, 1940). The degrees of freedom can be calculated as $N-1$ (where N is the sample number). In this instance, there are two treatments, namely mulch and fertilizer. The mulch treatment has two levels (i.e. mulch and no mulch), whilst the fertilizer treatment has three levels (i.e. full, half and zero fertilizer). Therefore, when testing the impact of mulch on yield and soil surface temperature, there is only one degree of freedom. When testing the impact of fertilizer and mulch on yield, there are five degrees of freedom.

Model evaluation is essential to ascertain model accuracy in simulating the observed trends, to evaluate the impact of calibrating the model with site-specific data and to compare results from previous studies (Krause *et al.*, 2005). Different statistical indicators exist, each with different strengths and weaknesses. Therefore, a number of statistical indicators are used to provide better insight into model performance.

The Pearson correlation coefficient (R) and its squared value (R^2), which is dependent on the number of observations (n), measure dispersion of observed and predicted data. R ranges from -1 to 1, with 1 indicating good agreement. This can be misleading because a model can under- or over-estimate observations and still have a high R^2 value (Krause *et al.*, 2005). Since R and R^2 are insufficient to evaluate model performance alone (Willmott, 1982), two additional indicators were used as described next.

The Root Mean Square Error (RMSE) quantifies the extent of differences between simulated and observed data. RMSE ranges from 0 to positive infinity, with positive infinity indicating

poor correlation. A limitation of the RMSE is that it does not differentiate between under- and over-estimation. Additionally, residual errors are squared, giving larger weight to higher values in the time series compared to lower values (Legates and McCabe, 1999).

Willmott's index of agreement (D) measures the degree to which observed data are approached by the predicted data. It overcomes the insensitivity of R^2 to under- and over-estimations by the model (Willmott, 1982). The index ranges from 0 to 1, with 1 indicating good agreement.

4 RESULTS AND DISCUSSION

In this section, the results obtained in this study are presented and discussed. The weather data is discussed (*cf.* **Section 4.1**), followed by measurements of soil water retention characteristics (*cf.* **Section 4.2**). The results of the Watermark sensor calibration are given in **Section 4.3**, along with the impact of mulching and fertilizer on, *inter alia*, soil water content and soil temperature (*cf.* **Section 4.4**), crop growth and final yield (*cf.* **Section 4.5**) and biodiesel yield (*cf.* **Section 4.6**). In **Section 4.7**, crop water use efficiency was estimated using AquaCrop for all treatments. The full fertilizer, non-mulched treatment simulated by AquaCrop was then compared to the simulation made by the SWB model. Model validation was achieved by comparing model simulations with observed data. Crop coefficients were then calculated from simulated model output.

4.1 Weather Data

Daily climate data from a nearby station (Bruyns Hill, approximately 4 km away) was obtained from the South African Sugar Research Institute (SASRI) website. The Bruyns Hill dataset was used to extend the Swayimane record as well as for comparison and patching purposes (*cf.* **Appendix 5**). Other records of daily data pertaining to maximum and minimum air temperature (T_{MAX} and T_{MIN}), solar radiation, relative humidity and wind speed were correlated to observed data in Bruyns Hill in order to acquire data from the beginning of the season until the weather station was functional (*cf.* **Appendix 5**). **Table 4.1** gives the minimum and maximum records of each of the above-mentioned weather variables, while the complete daily weather data is presented in **Appendix 6**.

Table 4.1: Maximum and minimum values for daily weather variables recorded at Swayimane over the trial period

Weather variable	Minimum	Date	Maximum	Date
T_{MAX} (°C)	15.2	14-Nov-15	38.8	24-Dec-15
T_{MIN} (°C)	4.4	04-Nov-15	20.7	25-Feb-16
Solar radiation ($MJ\ m^{-2}\ day^{-1}$)	2.2	08-Mar-16	30.1	01-Dec-15
Relative humidity max. (%)	18.4	06-Nov-15	97.0	02-Mar-16
Relative humidity min. (%)	14.0	05-Nov-15	96.3	06-Dec-15
Wind speed ($m\ s^{-1}$)	0.6	10-Nov-16	3.5	27-Nov-15
Reference crop ET (mm)	0.7	14-Nov-15	8.2	24-Dec-15

4.2 Soil Water Characteristics

This section details the results of estimated soil water characteristics. Soil water retention parameters, *viz.* saturation, field capacity, permanent wilting point and saturated hydraulic conductivity are required by the AquaCrop and SWB models.

4.2.1 Estimation of saturation

The controlled outflow pressure method (*cf.* **Section 3.5.4.4**) provided the output of final pressure head (cm) and volumetric soil water content ($\text{cm}^3 \text{cm}^{-3}$). Saturation (i.e. total porosity) was estimated from the volumetric water content when the soil matric potential was at 0 kPa.

4.2.2 Estimation of field capacity

The soil water retention curve at 0.15 m depth was used to derive an equation from which field capacity (θ_{33}) was obtained. The retention curves representing the soil depths are shown in **Appendix 7**. The trend lines that provided the highest R^2 values were selected. The measured saturation values (at 0 cm head) and calculated field capacity values (at 330 cm head) for the different depths are shown in **Table 4.2**. A value of $0.59 \text{ cm}^3 \text{cm}^{-3}$ at saturation is high for a sandy clay soil (as observed at 0.15 m depth). A peak value of the volumetric water content at saturation is given as 50% in AquaCrop (Steduto *et al.*, 2012) and 48% is given by SPAW. Therefore, this implies an error during laboratory measurement of this value.

Table 4.2: Soil water retention characteristics estimated using the controlled outflow method

Depth (m)	Saturation (%)	Field capacity (%)	Permanent wilting point (%)	Saturated hydraulic conductivity (mm day ⁻¹)	Bulk density (g cm ⁻³)
0.15	59.0	40.7	-	-	1.36
0.30	49.3	43.9	-	-	1.35
0.60	49.1	42.9	-	-	1.32
0.90	54.2	52.0	-	-	1.30

Note: - indicates values that could not be estimated.

4.2.3 Estimation of bulk density

Bulk density was calculated by measuring the mass of solids and the volume of the core used to obtain undisturbed soil samples, as detailed in **Section 3.5.4.2**. However, this approach resulted in low estimates of bulk density, especially for the topsoil. This may be attributed to land preparation that took place before soil samples were acquired from the field, which may

have caused changes to the topsoil structure. Therefore, the bulk density estimates generated from the outflow pressure method were deemed more appropriate for use in further analyses as these were obtained from undisturbed soil cores that were obtained from the drainage pit (*cf.* **Table 4.3** below for results).

4.2.4 Estimation of permanent wilting point

As noted in the methodology (*cf.* **Section 3.5.4.5**), the failure of the high-pressure compressor in the UKZN soils laboratory prevented the measurement of soil water content at -1500 kPa. Using soil texture as input, values for the soil water content at saturation (θ_0), field capacity (θ_{33}) and permanent wilting point (θ_{1500}) were estimated using the SPAW and RETC programs (*cf.* **Table 4.3**). In addition, soil bulk density (ρ_b) was estimated using the SPAW model.

Table 4.3: Soil water retention characteristics estimated using the SPAW and RETC software utilities

Depth (m)	Saturation (%)	Field capacity (%)	Permanent wilting point (%)	Saturated hydraulic conductivity (mm day ⁻¹)	Bulk density (g cm ⁻³)
SPAW					
0.15	47.8	35.8	23.8	97.5	1.38
0.30	44.8	36.8	25.4	30.5	1.46
0.60	48.0	40.7	28.7	24.4	1.38
0.90	47.3	44.3	32.9	6.1	1.33
RETC					
0.15	38.0	35.6	26.6	-	-
0.30	46.7	46.2	29.8	-	-
0.60	44.8	43.5	29.8	-	-
0.90	56.4	55.8	35.9	-	-

Note: - indicates values that could not be estimated.

Both approaches produced estimates which correlated fairly well with measured data (except at the 0.9 m depth). In addition, the two approaches produced relatively similar estimates of permanent wilting point, with RETC simulating slightly higher values than SPAW. Although, estimates made by RETC were based on laboratory measurements, the permanent wilting point simulated by SPAW was deemed more appropriate than RETC. This was based on the interpretation of volumetric water content, whereby values of saturation and field capacity

estimated by RETC were unrealistically similar. This outcome is unlikely for a sandy clay soil, as mentioned previously in **Section 4.2.2**.

4.3 Calibration of Watermark Sensors

This section details results for the calibration of soil Watermark sensors for temperature sensitivity when converting resistance values to matric potential (*cf.* **Section 4.3.1**). Furthermore, results for the conversion of matric potential to volumetric water content is described in **Section 4.3.2**.

4.3.1 Conversion of sensor resistance to matric potential

The calibration equations developed by Thomson and Armstrong (1987), Shock *et al.* (1998), Allen (2000) and CSI (2013) were plotted using Watermark resistance values from 0 to 30 k Ω as shown in **Figure 4.1**. The original equation developed by Irrometer Co. (i.e. **Equation 7.3**) was not plotted since it is no longer used (Chard, 2002).

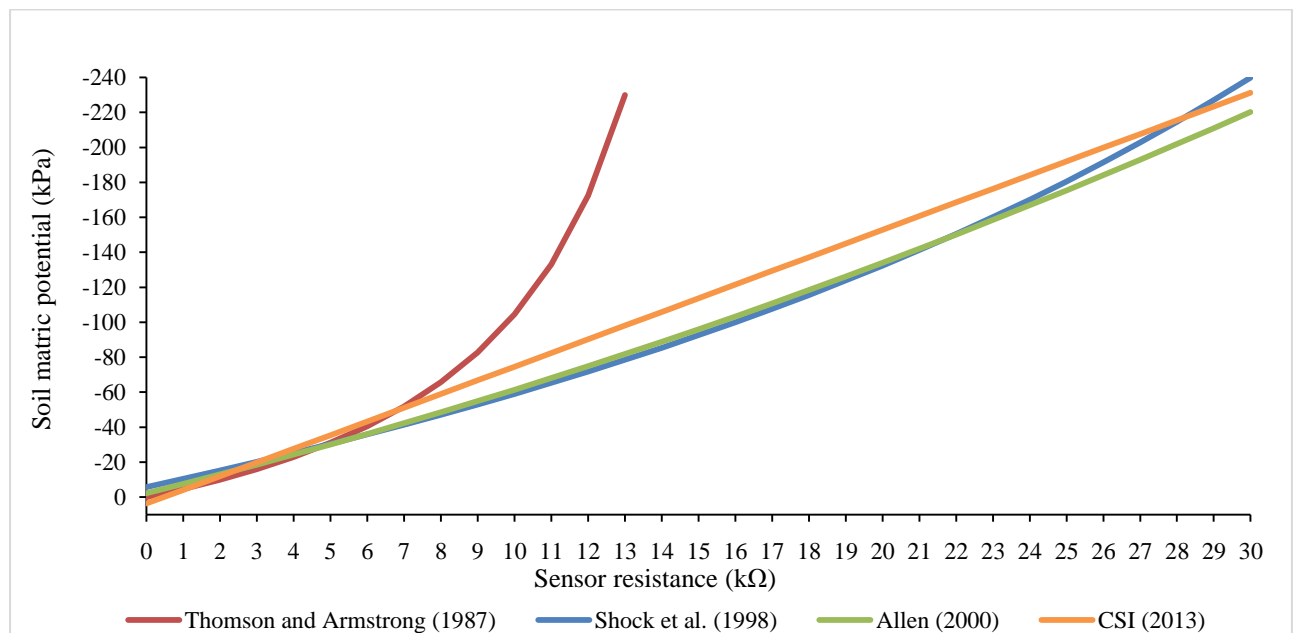


Figure 4.1: Evaluation of four different equations to estimate soil matric potential from Watermark sensor resistance ranging from 0-30 k Ω

The equation developed by Shock *et al.* (1998) is now recommended by Irrometer Co. (Riverside, California USA), which is programmed into their Watermark digital meter (Chard, 2002; Thompson *et al.*, 2006). Although a calibration temperature of 21°C was originally

adopted by Irrrometer Co., a soil temperature of 24°C is now used as noted by Allen (2000) and Chard (2002). The Shock *et al.* (1998) equation also uses a calibration temperature of 24°C. Hence, it was unclear why Campbell Scientific still use 21°C as the recommended calibration temperature for their Watermark sensors (CSI, 2013). The Campbell Scientific equation (CSI, 2013) over-estimates soil matric potentials values in the range 3-28 kΩ when compared to the Shock *et al.* (1998) equation and the Allen (2000) quadratic equation.

The CSI (2013) equation also predicts positive values below 0.6 kΩ which is deemed incorrect (*cf.* **Figure 4.2**). The latter is theoretically impossible since by definition, matric potential is zero for a saturated soil and negative for an unsaturated soil. At 0 kPa, the soil is at saturation, meaning the total pore space in the soil is saturated by water and water is easily taken up by the crop. At the other extreme of -1500 kPa, water is unavailable for crop uptake and the crop is said to be at the permanent wilting point. Finally, Chard (2002) reported that the equation is “outdated” and thus, was not used in this study.

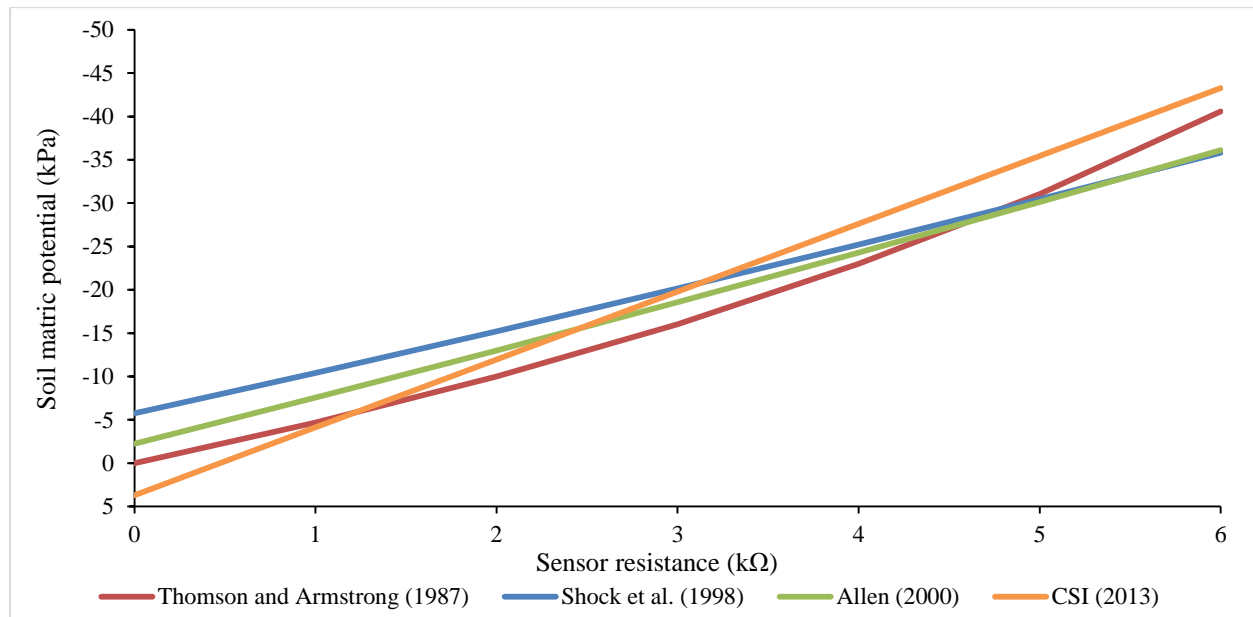


Figure 4.2: Evaluation of four different equations to estimate soil matric potential from Watermark sensor resistance ranging from 0-6 kΩ

Thompson *et al.* (2006) reported that the Thomson and Armstrong (1987) equation was developed for the original Watermark sensor (model 200). It is clear from **Figure 4.1** that the equation fails for sensor readings above 13 kΩ. For resistance readings of 18 kΩ and above, the equation gives positive soil matric potential values. It is therefore recommended that this equation is not used for the entire range of sensor resistance values.

Thompson *et al.* (2006) concluded that for soil matric potential readings from -30 to -80 kPa, the Shock *et al.* (1998) equation or the Allen (2000) quadratic equation perform best. From **Figure 4.1**, these two equations give similar results (within ± 3 kPa) up to 24 k Ω . Soil matric potential estimates are almost identical for resistance values of 5 k Ω (-30 kPa) and 6 k Ω (-36 kPa) at 24°C.

The largest discrepancy in the four equations occurs when the soil is close to saturation (i.e. resistance $R < 1$ k Ω). From **Figure 4.2**, the Allen (2000) quadratic equation is recommended for resistance values from 0-6 k Ω . This equation provides similar results to the equation recommended for use by Irrometer Co., i.e. Shock *et al.* (1998) equation. However, the Thomson and Armstrong (1987) equation is the only equation which estimates 0 kPa when there is no resistance (i.e. 0 k Ω). Since it is difficult to use two different equations in a data logger to estimate soil matric potential, the quadratic equation proposed by Allen (2000) (i.e. **Equation 7.7** in **Appendix 4**) was used to derive soil matric potential from Watermark sensor resistance as this equation is the most appropriate for the wide range of soil matric potential observed in this study, for reasons mentioned above.

4.3.2 Conversion of matric potential to volumetric water content

The derivation of volumetric water content from the soil matric potential is detailed next. Ideally, sensors that directly measure soil water content (such as TDR probes) should be installed in conjunction with Watermark sensors for calibration purposes. However, due to budget constraints, the direct measurement of soil water content was not included in this study. Therefore, the conversion of soil Watermark sensor matric potential to volumetric water content was achieved using:

- regression curves of volumetric water content (obtained from gravimetric soil water content) vs corresponding matric potential, as well as
- the van Genuchten (1980) equation, at the respective soil depths.

4.3.2.1 The regression equation

Since soil matric potentials are negative, they were converted to matric pressure heads (where -1 kPa = 10.2 cm). The plotted regression curves gave fairly good R^2 values, ranging from 0.77 to 0.87. The displayed equation was then used to convert soil water pressure head to volumetric water content. The same process was followed for the 0.4 m, 0.6 m, 0.8 m and 1.0 m depths (*cf.* **Appendix 8** for regression curves). The same regression curves were applied to the sensors

in the field plots, where the sensors installed at 0.15 m and 0.3 m were represented by the 0.2 m and 0.4 m regression curves derived from soil samples taken from the drainage pits.

4.3.2.2 The van Genuchten (1980) equation

The van Genuchten (1980) equation has been widely applied to estimate soil water retention and hydraulic conductivity of unsaturated soils. Most authors report that the model provides high correlation between simulations and observations (Kanzari *et al.*, 2012; Bourazanis *et al.*, 2016). In this study, the Rosetta Lite (v1.1) model, which is built into the RETC model, was used to estimate the five van Genuchten (1980) parameters (i.e. θ_R , θ_S , α , n , m ; refer to **Section 3.5.4.5**) that are required to calculate soil water content (*cf.* **Table 4.4**). The input data included the relative sand, silt and clay fractions, bulk density and volumetric soil water content at field capacity as estimated from the controlled outflow method.

Table 4.4: Input parameters used in the van Genuchten (1980) equation, as estimated by the Rosetta program

Soil Depth (m)	θ_R (cm ³ cm ⁻³)	θ_S (cm ³ cm ⁻³)	α	n	m
0.15	0.0845	0.4775	0.0089	1.3076	0.2352
0.30	0.0902	0.4923	0.0093	1.2751	0.2157
0.60	0.0900	0.5054	0.0166	1.2059	0.1707
0.90	0.1036	0.5317	0.0106	1.2208	0.1809

The log regression curve and van Genuchten (1980) equations provided similar trends in soil water content, although the van Genuchten (1980) equation produced lower estimates of volumetric soil water content relative to the log regression (*cf.* **Figure 4.3**). For the interpretation of volumetric water content, the field capacity estimates by the controlled outflow method was used, while the permanent wilting points modelled by SPAW were used. The regression curves provided a better fit between soil water content and the gravimetric points at all depths (*cf.* **Appendix 9**), compared to the van Genuchten (1980) equation. However, this can be expected as the regression curve was derived from the gravimetric water content. The log regression was used for further analysis as it was closest to the gravimetric water content.

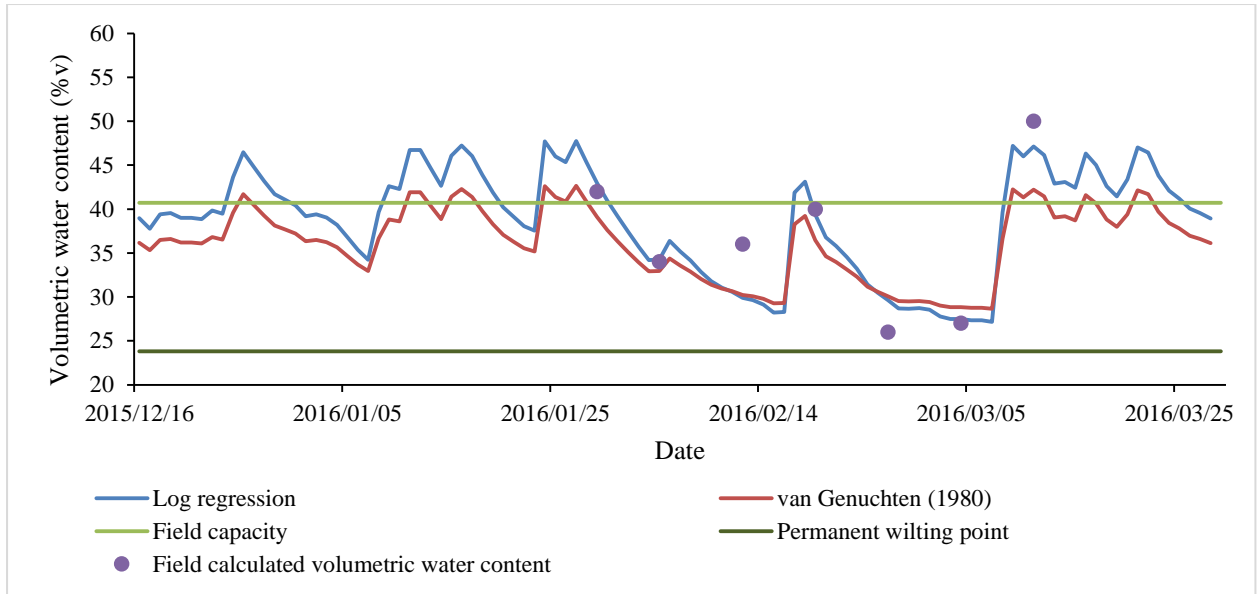


Figure 4.3: Comparison of the regression equation approach to the van Genuchten (1980) equation for predicting volumetric water content at the 0.2 m soil depth

4.4 Mulching Effects on Soil Moisture Content and Soil Temperature

A number of studies have confirmed that mulching improves soil water content through the reduction of soil water evaporation (Ritchie and Basso, 2008; Sinkevičienė *et al.*, 2009), which implies more water available for use by the crop. Additionally, mulching is believed to regulate soil water fluctuations by moderating soil surface temperature (as discussed in **Section 2.3.2.1**), which is favourable for the growth and development of most crops. The benefits of mulching are presented in the three sections that follow.

4.4.1 Soil water content in mulched vs non-mulched soil

Mulching improved soil water content (*cf.* **Figure 4.4**). This was especially the case in the shallowest soil depth. Soil water stress was assumed to occur at 50% of plant available water. Soil water content in the non-mulched plots fluctuated from field capacity to below the stress point. On the contrary, soil water content in the mulched plots was relatively further from the stress point and only decreased below the stress point on one occasion. Furthermore, the mulched treatments maintained higher soil water content during prolonged intervals in which no rainfall occurred. Therefore, mulching reduced fluctuations in soil water content.

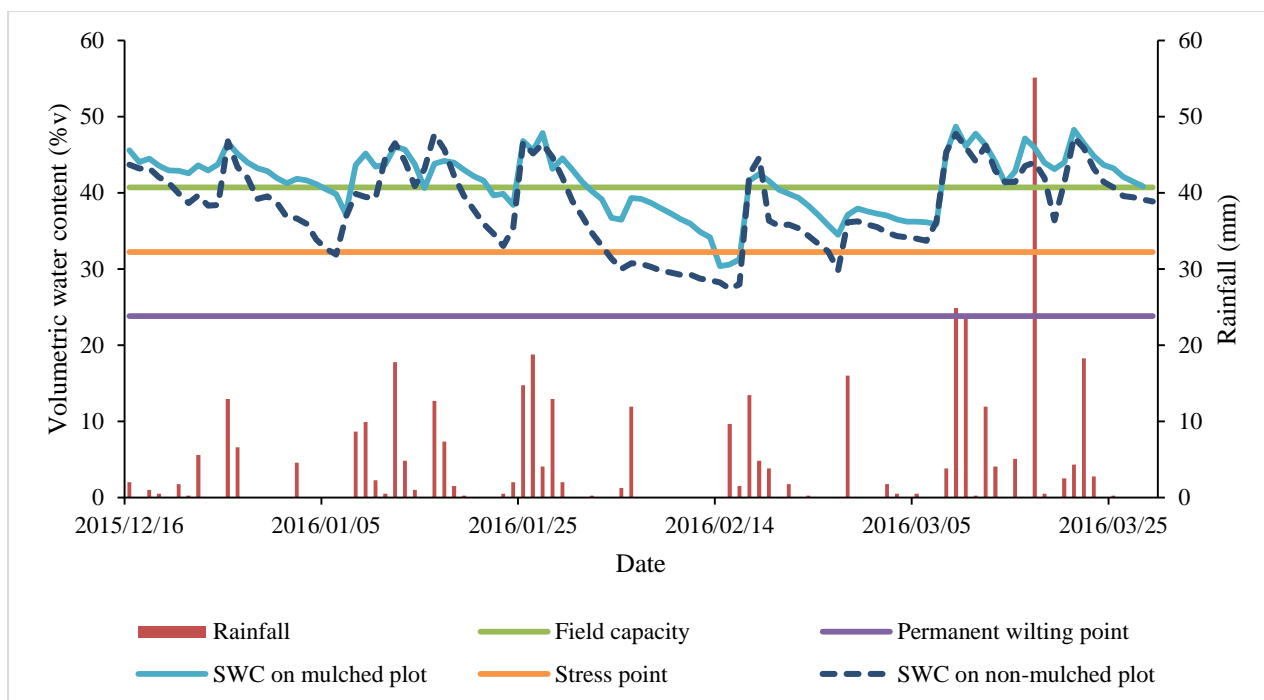


Figure 4.4: Comparison of changes in soil water content between a 0.15 m depth mulched and non-mulched treatment for the full fertilizer treatment

4.4.2 Soil temperature in mulched vs non-mulched plots

While some studies have reported an increase in soil surface temperature (Ramakrishna *et al.*, 2006), several studies, including this study, have reported that mulching with straw mulch reduces soil surface temperature (Giller *et al.*, 2009; Molden *et al.*, 2010; Obalum *et al.*, 2011). **Figure 4.5** shows soil surface temperature in a mulched vs non-mulched plot. Mulching significantly affected soil surface, with the mean of 17.26 and 18.80 °C for the mulched and non-mulched treatments, respectively. The non-mulched surface starts off with a higher surface temperature, as expected. The highlighted area represents a period where the thermocouple was detached from the soil surface during data collection (circled area in **Figure 4.5**). before it was corrected. When performing an ANOVA, the period in which the thermocouple detached was excluded. Although the thermocouple was detached for a long period during the growing season, the temperature remained cooler in the mulched plots even after harvest.

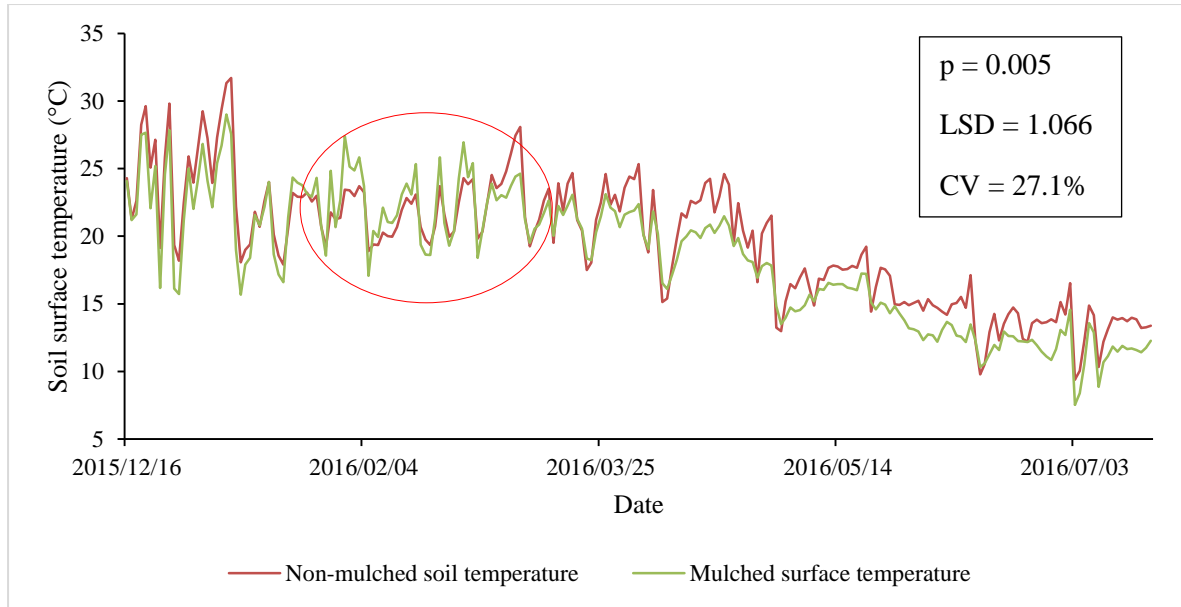


Figure 4.5: Soil surface temperature between a mulched and non-mulched treatment (Circled area indicates excluded period in ANOVA analysis due to sensor detachment from the soil surface)

4.4.3 Subsoil temperature variation

As a general rule of thumb, soil temperature should be fairly constant over the growing season, decreasing slightly with depth. Irmak *et al.* (2016) reported seasonal changes of approximately 2.8 °C (5°F) in soil temperature at 15 cm (6 in). This fluctuation decreased to about 1.7 °C (3.1°F) at lower depths. The topsoil temperature fluctuates the most due to the close interaction with weather variables. Due to shading effects, the topsoil surface temperature decreases as the canopy develops (Irmak *et al.*, 2016). Similar findings were obtained in this study, whereby the seasonal change in temperature was recorded as 2.5 °C in the topsoil and an average of 1 °C at the lower depths.

The sub-soil temperatures showed interesting trends in heat assimilation from the topsoil to the subsoil and a clear distinction between the changes in season from summer to winter (**Figure 4.6**). The initial trend shows high temperature fluctuations, especially at the shallowest depth. This period coincides with summer, in which high air temperatures prevail, explaining the high soil surface temperatures in summer. Over time, the heat is assimilated from the topsoil into the deeper soil layers and a time lag is also visible. The deepest soil layer is the coolest and has the least temperature fluctuations. During mid-March, the trend begins to reverse due to lower air temperatures. In winter, the shallow soil profile is the coolest as a result of low air

temperatures, while the deepest layer is the warmest as it is insulated by the topsoil through heat retention.

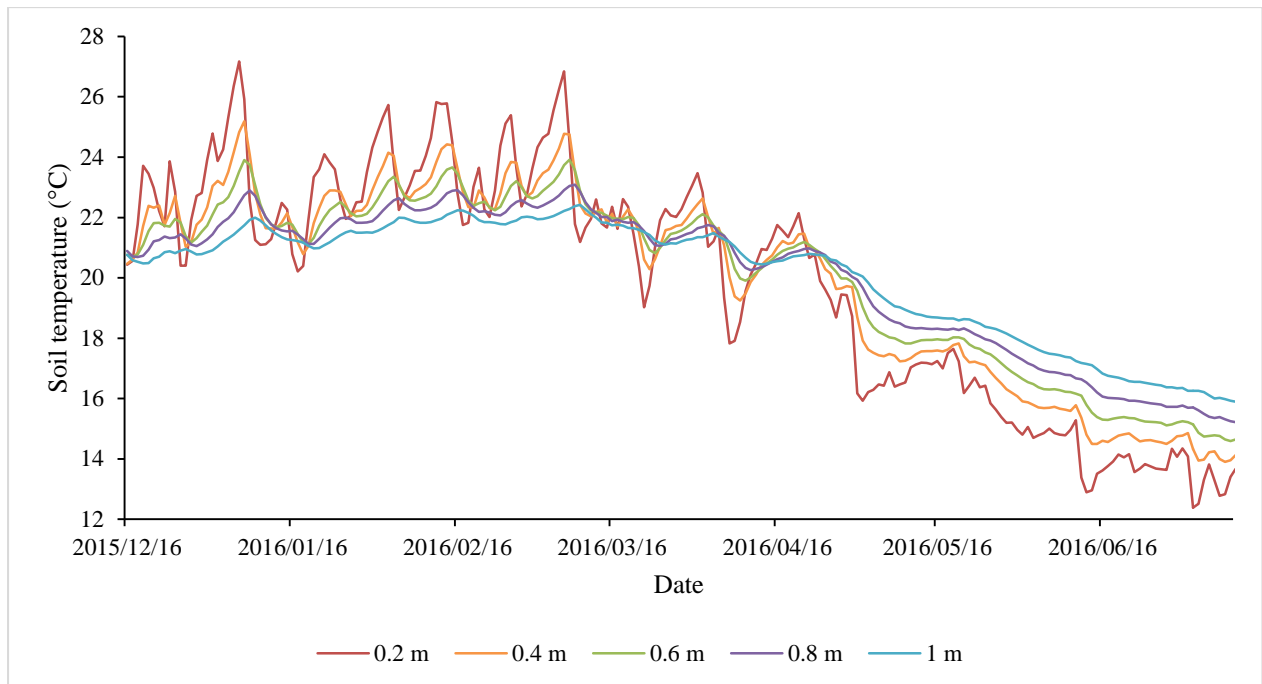


Figure 4.6: Subsoil temperature variation across different soil depths

4.5 Total Crop Yield

It was hypothesized that increased levels of fertilizer coupled with mulch would produce the highest yield. Additionally, mulching is believed to reduce soil surface temperature and improve soil water content, especially in periods of prolonged dry conditions in which no rainfall occurs. However, although statistically insignificant, contrary results were observed in that the non-mulched plots produced higher yields compared to mulched plots as shown in **Table 4.5**. The results obtained from the study pertaining to the impact of fertilization and mulching on crop growth parameters and the final yield are discussed next in more detail.

Table 4.5: Total biomass and yield obtained for the different treatments

Mulching Treatment	Fertilizer level	Biomass (t ha ⁻¹)	Yield (t ha ⁻¹)	Harvest index (%)
	(%)			
Non-mulched	100	4.98	1.61	32
Non-mulched	50	4.65	1.48	32
Non-mulched	0	4.18	1.21	29
Mulched	100	2.89	0.77	27
Mulched	50	2.36	0.63	27
Mulched	0	2.11	0.67	32

Similar findings have been reported in the literature, whereby mulching does not have a significant impact on soybean yield (Moore *et al.*, 1994; Sørensen *et al.*, 2004). This may have resulted from poor nodule formation. Similar findings were observed by Moore *et al.* (1994) where mulching was reported to cause poor nodule formation in soybean. This can affect the growth and yield when residual nitrogen is not available. The effects of poor nodule formation can be ameliorated by seed inoculation of soybean seeds with *Bradyrhizobia japonicum* bacteria.

Nitrogen availability may have been worsened by nitrogen immobilization caused by decaying straw mulch, as observed in previous studies (Wicks *et al.*, 1994; Cheshire *et al.*, 1999). The processes involved in nitrogen immobilisation is believed to result from a high demand of nitrogen by soil microorganisms in order to decompose the mulch, resulting in N unavailability for uptake by the crop (Siczek and Lipiec, 2011). Furthermore, the cooling effect of the mulch layer could have contributed to the observed yield reduction since lower soil temperature can hinder nodulation (Siczek and Lipiec, 2011). Symptoms of nitrogen deficiency and poor soybean nodulation are yellowing of older leaves and stunted growth (ASGROW, 2015), as was observed in this study (**Figure 4.7**). In Baynesfield, a yield of 5.28 t ha⁻¹ was reported when harvesting was done mechanically (Moyo and Savage, 2014, cited by Kunz *et al.*, 2015). The highest yield obtained in this study of 1.61 t ha⁻¹ was 54% less than that which was obtained in a commercial farming environment.



Figure 4.7: The observed yellowing of older leaves and stunted growth of soybean for the mulched (foreground) treatment

4.5.1 *Soil nutrient status*

An analysis of soil chemical properties was done before planting and after harvest in order to assess changes in soil nutrient levels. The soil test included, *inter alia*, soil organic carbon as well as the NPK levels to determine the required nutrient amount (**Table 4.6**). The organic carbon level of the mulched treatments was higher after harvest than those of the non-mulched treatments. This can be attributed to the decomposition of straw mulch. Duiker and Lal (1999) and Saroa and Lal (2003) also reported higher levels of soil organic carbon where crop residues were applied.

The soil test represents the amount of available nutrients in the soil solution, while the target soil test is a measure of the necessary nutrient input in order to achieve a certain target yield. The Potassium (K) test after harvest showed higher levels than was applied. This increase in K after harvest was greater in the mulched treatments than in the non-mulched treatments. This is believed to result from leaching of K from the mulch into the soil solution. Due to its mobility, K can be lost from crop residue by leaching (Sharma and Sharma, 2013). These results are in agreement with some authors who reported that crop residues can provide exchangeable K in soil (PPI, 1998; Li *et al.*, 2014; Heidari and Jalili, 2016).

Table 4.6: Soil fertility results before planting and after harvest as determined by the Soil Analytical Service Laboratory at the Cedara College of Agriculture

Treatment	% organic carbon	% Nitrogen	P (mg g ⁻¹)		K (mg g ⁻¹)	
			Sample soil test	Target soil test	Sample soil test	Target soil test
At planting	3.0	0.21	0.005	0.012	0.060	0.096
At harvest						
NM 100	3.17	0.19	0.001		0.177	
NM 50	3.97	0.25	0.012		0.099	
NM 0	3.47	0.21	0.008		0.082	
M 100	3.63	0.24	0.008		0.305	
M 50	4.03	0.22	0.008		0.134	
M 0	4.07	0.24	0.006		0.108	

Note: NM = non-mulched; M = mulched; 100, 50 and 0 represent the fertilizer level (as %)

4.5.2 Soil fertility

The impact of soil fertility was assessed on crop growth parameters (i.e. plant height, leaf number, stomatal conductance and leaf area index) and crop yield parameters (i.e. grain yield, total biomass and harvest index). Only statistically significant treatments are presented, unless stated otherwise. The LSD was carried out only if treatments had a statistically significant impact ($p < 0.05$). The coefficient of variation measures the deviation of treatments relative to the mean.

4.5.2.1 Crop growth parameters

Soil fertility had a significant effect on leaf area index (**Figure 4.8**) and canopy cover (**Figure 4.9**). A similar trend was observed for leaf area index (LAI) and canopy cover (CC), which was expected since LAI is directly proportional to CC according to the equation presented by Mabhaudhi *et al.* (2014) (*cf.* **Equation 3.5** in **Section 3.7**).

For the non-mulched treatments, the full fertilizer level had the highest LAI and CC, followed by the half fertilizer treatments. This was expected because of the known effects of P and K on several plant processes, such as enzyme activity, reproductive growth, uptake and transfer of certain nutrients, and regulation of water vapour and carbon dioxide through stomatal control, as was mentioned in **Section 2.3.2.2**. Therefore, higher inputs of K and P had favourable effects

on canopy expansion. These findings are in accordance with most research, in which higher nutrient inputs are reported to have beneficial impacts on crop growth parameters (Snyder, 2000; Win *et al.*, 2000; Malik *et al.*, 2006; Bellaloui *et al.*, 2015a; Bellaloui *et al.*, 2015b). Although not statistically significant, the LAI for the mulched treatments are presented to allow comparison with the non-mulched treatments.

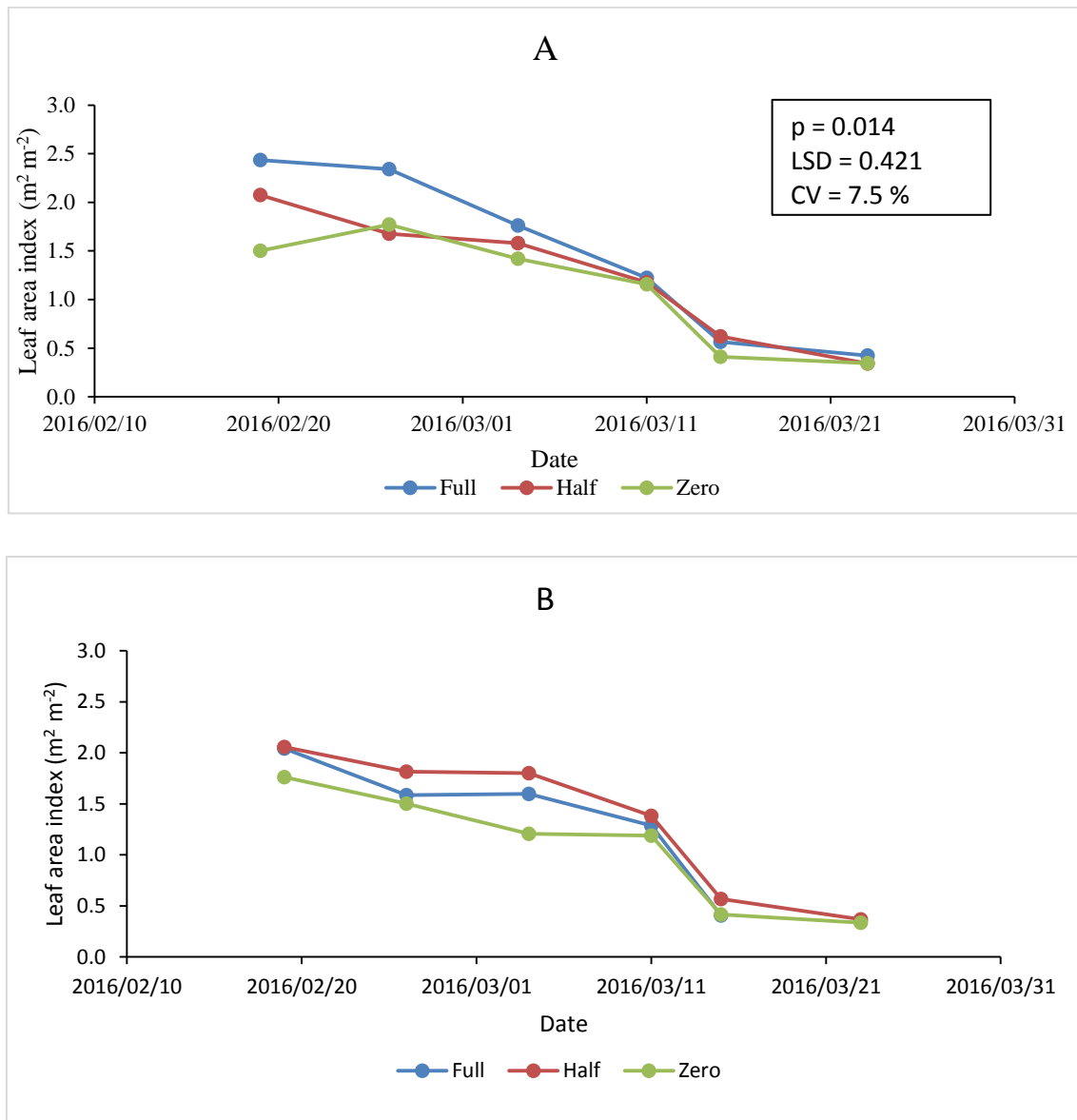


Figure 4.8: The impact of soil fertility on average leaf area index on non-mulched (A) and mulched (B) treatments

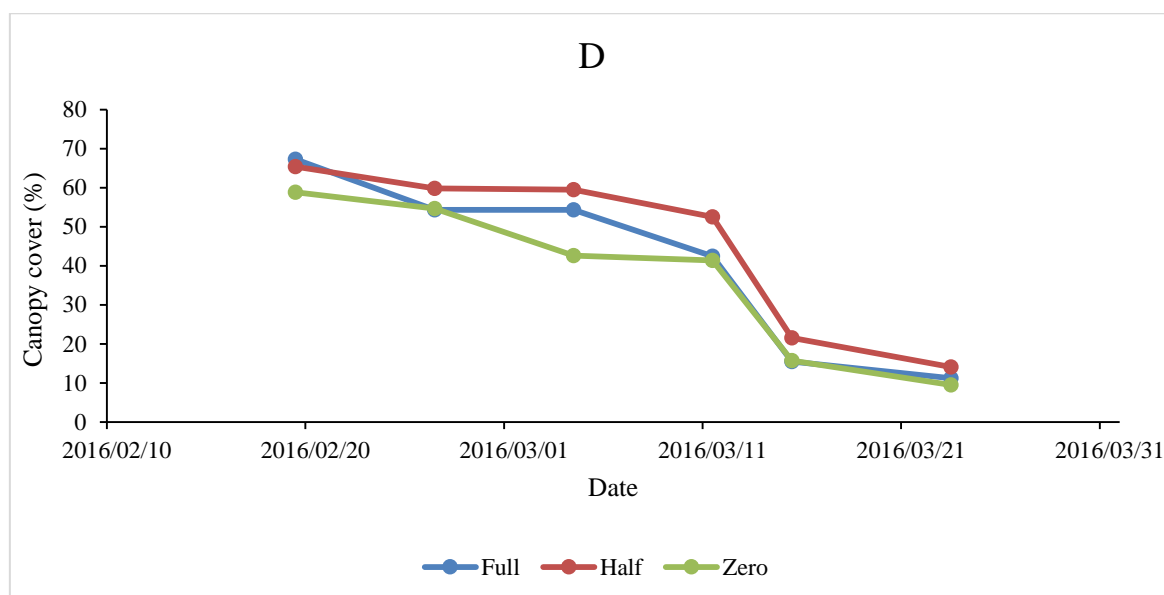
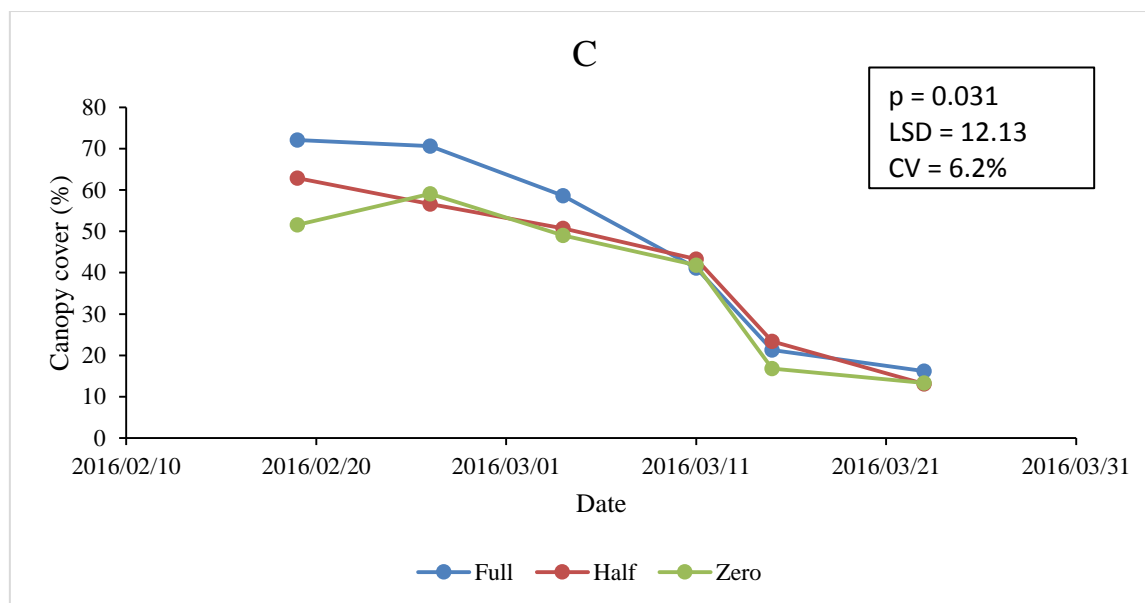


Figure 4.9: The impact of soil fertility on average canopy cover on non-mulched (C) and mulched (D) treatments

Biomass accumulation is presented in **Figure 4.10**. The non-mulched treatments accumulated more biomass throughout the growing season when compared to the mulched treatments. This was not the expected outcome since mulching improved soil water content (*cf.* **Figure 4.4**), which is favourable for crop growth and development. However, as discussed previously in this study, mulching resulted in nitrogen immobilisation which retarded crop growth and hence, biomass accumulation in the mulched plots. As can be seen in **Figure 4.10 (E)** on the 20th of February 2016, biomass accumulation of the zero fertilizer treatment was higher than biomass

accumulation under the half and full fertilizer treatment. This is unlikely and was attributed to an erroneous measurement of biomass accumulation.

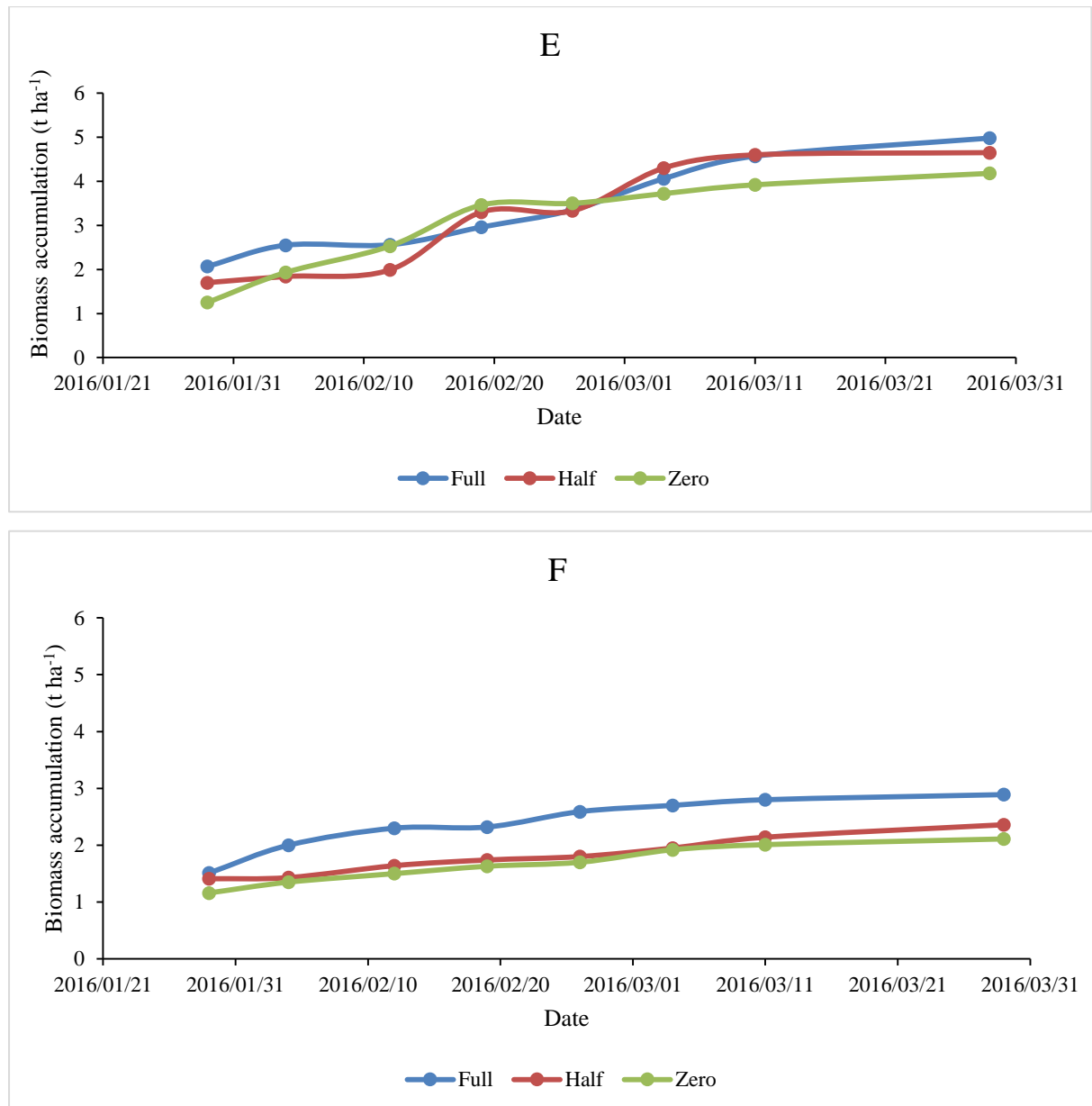


Figure 4.10: Biomass accumulation for the non-mulched (E) and mulched treatments (F)

Stomatal conductance is the measure of the diffusion of carbon dioxide into and water vapour out of the leaf (Mabhaudhi, 2012). When stomata are open, carbon dioxide flows into the leaves and water vapour is released (Molden *et al.*, 2010). This process facilitates crop photosynthesis. Additionally, the outflow of water vapour is necessary for cooling the plant and mobilizing soil nutrients. Stomatal conductance is reduced under water-limiting conditions, thereby limiting transpiration and photosynthesis, which may affect biomass production (Molden *et al.*, 2010).

When leaves fail to maintain turgor as a result of severe water stress, temporary wilting occurs. If the crop is watered or the evaporative power of the atmosphere is reduced, turgor can be restored, failing which the plant wilts permanently (White, 2003).

Stomatal conductance was significantly affected by soil fertility (*cf.* **Figure 4.11**). The full and half fertilizer treatments had higher stomatal conductance when compared to the zero fertilizer treatment. This is believed to be caused mainly by Potassium (K), rather than Phosphorous (P) application. Potassium is known to regulate carbon dioxide and water vapour movement between the plant and the atmosphere through stomatal control (Snyder, 2000). Therefore, higher inputs of K encourage higher transpiration rates and stomatal conductance, as K is the driving force for osmotic changes.

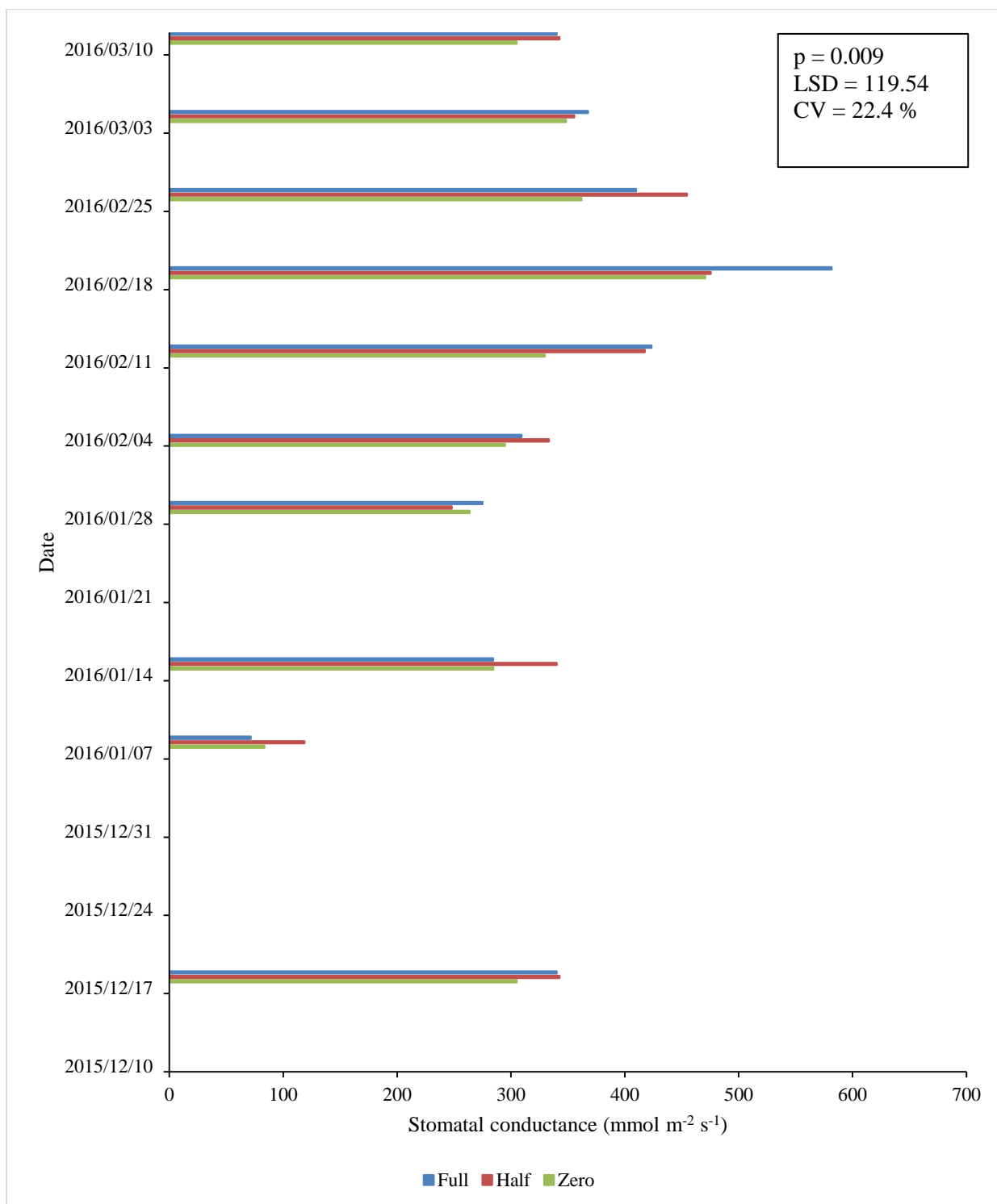


Figure 4.11: The average response of stomatal conductance to varying soil fertility levels

4.5.2.2 Crop yield parameters

Soil fertility had a significant impact on the yield and harvest index at the 90% and 95% confidence intervals, respectively. As anticipated, the full fertilizer treatments in both the mulched and non-mulched treatments produced the highest yield (**Figure 4.12**).

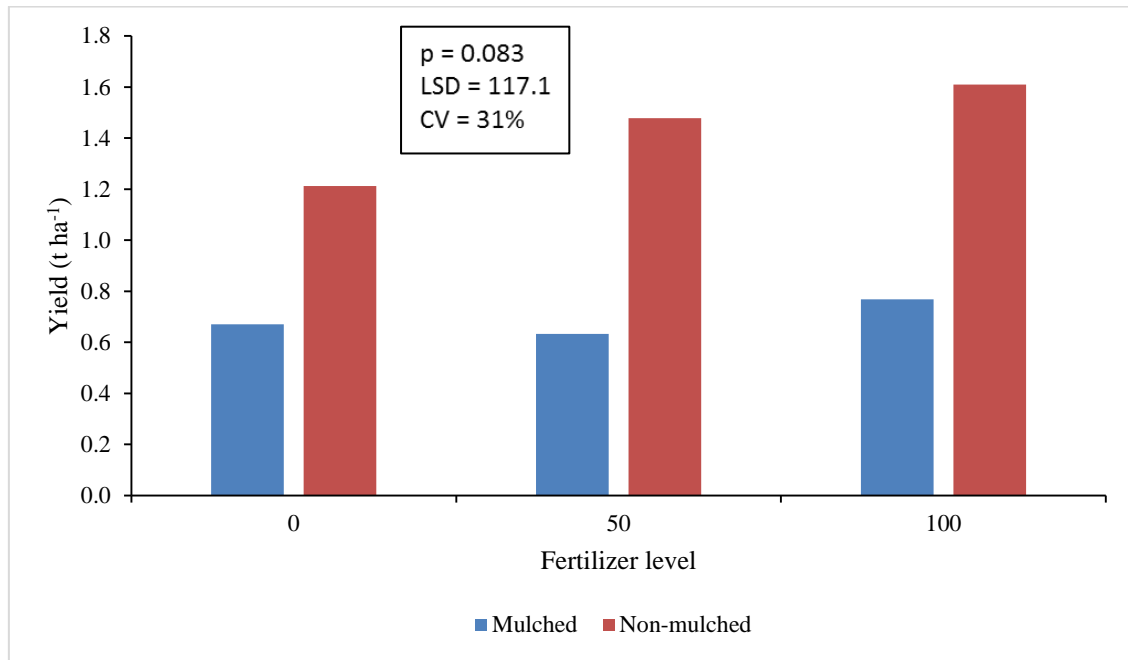


Figure 4.12: The impact of soil fertility and mulch on soybean yield

The harvest index (HI) relates the final yield to the total biomass produced. Since HI is directly proportional to yield, high HI indicates a greater portion of the biomass is converted to yield. Therefore, a high biomass and HI are favourable. The HI for the different treatments are presented in **Figure 4.13** below. Generally, the non-mulched treatments produced a higher HI than the mulched plots. This was not the expected response and can be attributed to the lower yields that were observed in the mulched plots, as mentioned previously.

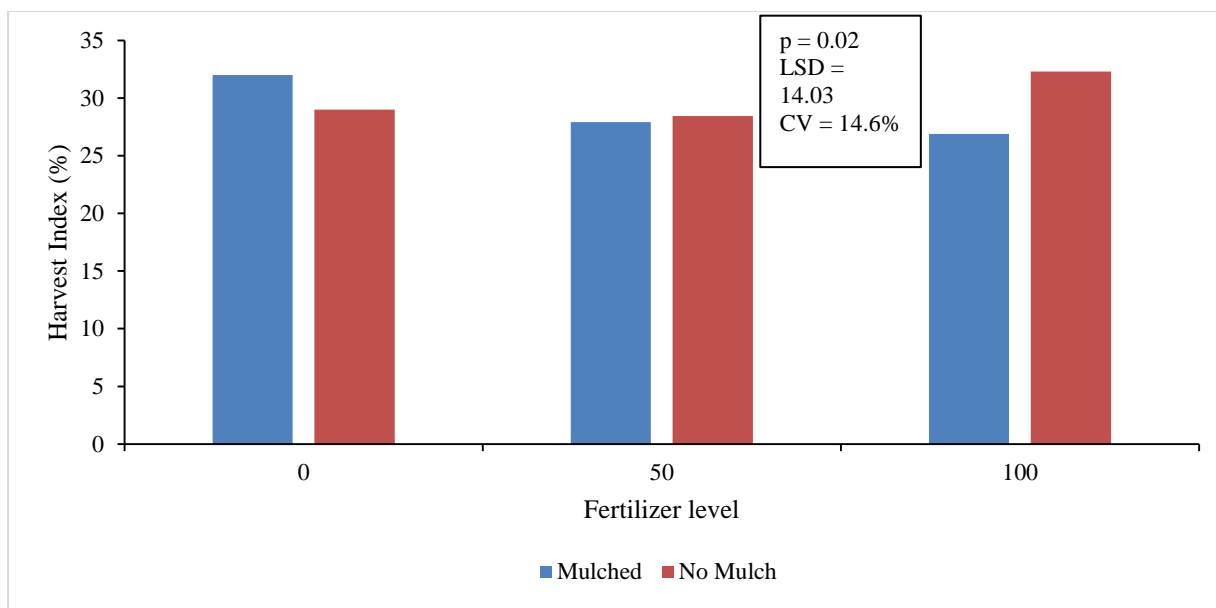


Figure 4.13: The impact of soil fertility on harvest index

4.5.3 Mulching

Mulching had a significant impact on stomatal conductance. In general, higher stomatal conductance rates were observed from the non-mulched treatments when compared to the mulched treatments (*cf.* **Figure 4.14**). Higher transpiration rates translate to more biomass production since stomatal closure reduces flow of carbon dioxide into the plant, causing a decline in photosynthesis and ultimately plant growth (Mabhaudhi, 2012). This contradicts the expected increase in stomatal conductance in mulched plots due to the higher soil water content (as discussed in **Section 4.4.1**).

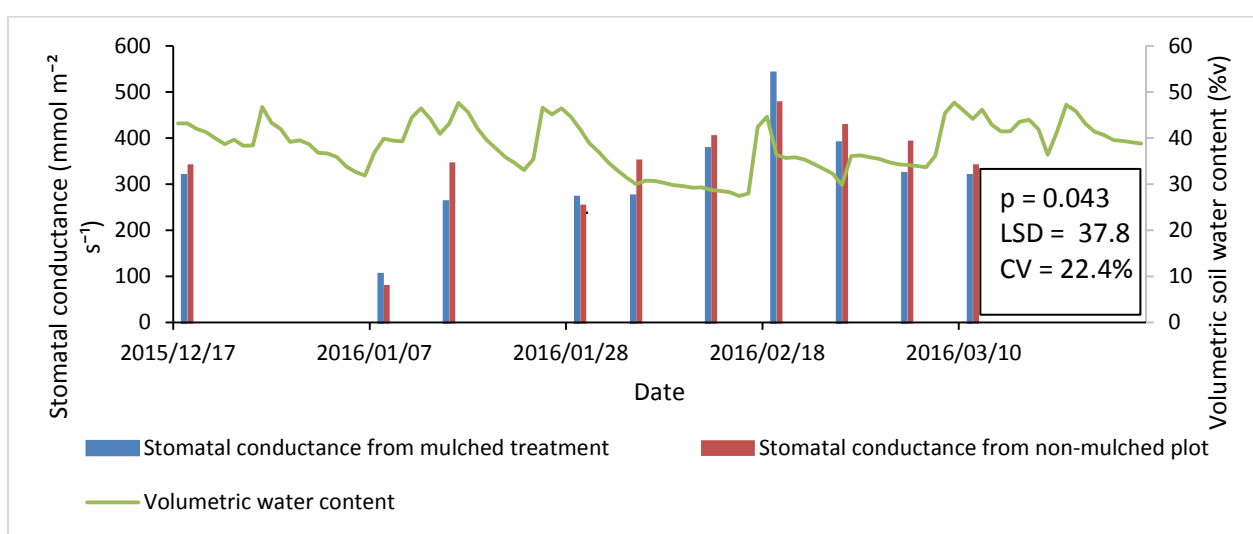


Figure 4.14: Impact of mulching on stomatal conductance in relation to soil water content

However, soil water content is not the only factor that affects stomatal conductance. Climatic factors such as solar radiation, relative humidity and concentration of carbon dioxide in the proximity of the stomata also influence stomatal conductance. The mulch surface may have created an artificial microclimate around the plants, altering net solar radiation, air temperature and relative humidity. Coupe *et al.* (2006) reported that increasing solar radiation increased stomatal conductance (assuming water was available in the soil). In addition, stomatal conductance has been reported to decrease with increasing relative humidity (Leuning, 1995). The mulch layer may have retained rain water, which would have evaporated back into the atmosphere and increased the ambient relative humidity, especially in the absence of wind. This could result in less water vapour being exchanged with the atmosphere and thus, reducing stomatal conductance in the mulched treatments.

Nitrogen (N) deficiency (as discussed at the beginning of **Section 4.5**) may have resulted in stunted growth (ASGROW, 2015) and thus, reduced stomatal conductance in the mulched treatments. This implies less leaf surface area from which stomatal conductance could take place compared to the non-mulched plots. Although not many authors have reported on the impact of N on stomatal conductance, Broadley *et al.* (2000) reported that low stomatal conductance was attributed to N deficiency in lettuce.

4.6 Biodiesel Yield

According to De Beer and De Klerk (2014; 2015), the average seed oil content of the soybean cultivar used (LS 6161R) in warm environments such as Swayimane is approximately 19.2%. In this study, below average values were mostly obtained, except in the 100% and 50% fertilizer treatments in the mulched plot (*cf.* **Table 4.7**). Although mulching reduced the overall yield, it resulted in higher seed oil content when compared to the non-mulched plots. This may have resulted from favourable lower temperatures for better seed quality, which was experienced in the mulched plots. Bellaloui *et al.* (2015a) also found that lower temperatures favoured higher seed oil content. The theoretical biodiesel yield was calculated using **Equation 3.7** in **Section 3.7.2**.

Table 4.7: Biodiesel use efficiency results for different treatments considered in this study

Mulching treatment	Fertilizer level (%)	Seed oil content (%)	Theoretical biodiesel yield (L ha⁻¹)	Biodiesel use efficiency (L m⁻³)
NM	100	17.4	289	0.063
NM	50	17.4	266	0.058
NM	0	16.7	209	0.047
M	100	20.5	163	0.039
M	50	21.0	137	0.034
M	0	17.8	123	0.324

Note: NM represents non-mulched treatments; M represents mulched treatments

The non-mulched plots resulted in higher theoretical biodiesel yield when compared to the mulched plots. There were insufficient degrees of freedom to run an ANOVA analysis to determine if a statistical difference in biofuel yield exists between mulching treatments. Furthermore, increasing soil phosphorous and potassium resulted in higher seed oil content in both mulched and non-mulched plots. These results are in agreement with other studies which have reported that increasing soil fertility resulted in higher seed oil content (Malik *et al*, 2006; Win *et al.*, 2010). The highest theoretical biodiesel yield of 289 L ha⁻¹ was obtained in the non-mulched, full fertilizer treatment. In a commercial environment (i.e. Baynesfield), a theoretical biodiesel yield of 654.3 L ha⁻¹ was obtained. The theoretical biofuel yield of the commercial farmer was 56% more than that of the smallholder farmer. The biofuel use efficiency (*cf.* **Section 2.3.3**) was calculated as the theoretical biodiesel yield per unit water used (L m⁻³) (*cf.* **Table 4.8** in **Section 4.7.1** for water use data). The biofuel use efficiency of 0.063 L m⁻³ was obtained under the non-mulched, full fertilizer treatment, while that of the commercial was reported as 0.14 L m⁻³. Therefore, the biofuel use efficiency of the smallholder farmer was 55% less than that of the commercial farmer.

4.7 Modelling of Crop Water Use and Yield

This section details the results obtained from the modelling component of this study. AquaCrop was used to estimate water use and crop yield for all treatments, from which estimates of water use efficiency were derived. The model was evaluated using canopy cover, biomass accumulation, final yield and total biomass. The SWB model was also used to estimate water use and crop yield of the non-mulched, fully fertilized treatment. The models were validated

by comparing the outputs with observed data. A comparison of results obtained from the two models is then made. Finally, crop coefficients derived from both models are presented.

4.7.1 *AquaCrop model*

Model evaluation is an important aspect of modelling studies since it allows the user to determine the accuracy of simulations made. A description of the statistical indicators used in this study was given in **Section 3.8.4**. In summary, a high R^2 , low RMSE and D-index closer to 1 indicate a good fit between simulated and observed data, which was achieved through a site-specific calibration. The crop parameters for soybean at Baynesfield produced significantly higher estimates of canopy cover and biomass accumulation than was observed (*cf.* **Figure 4.15**).

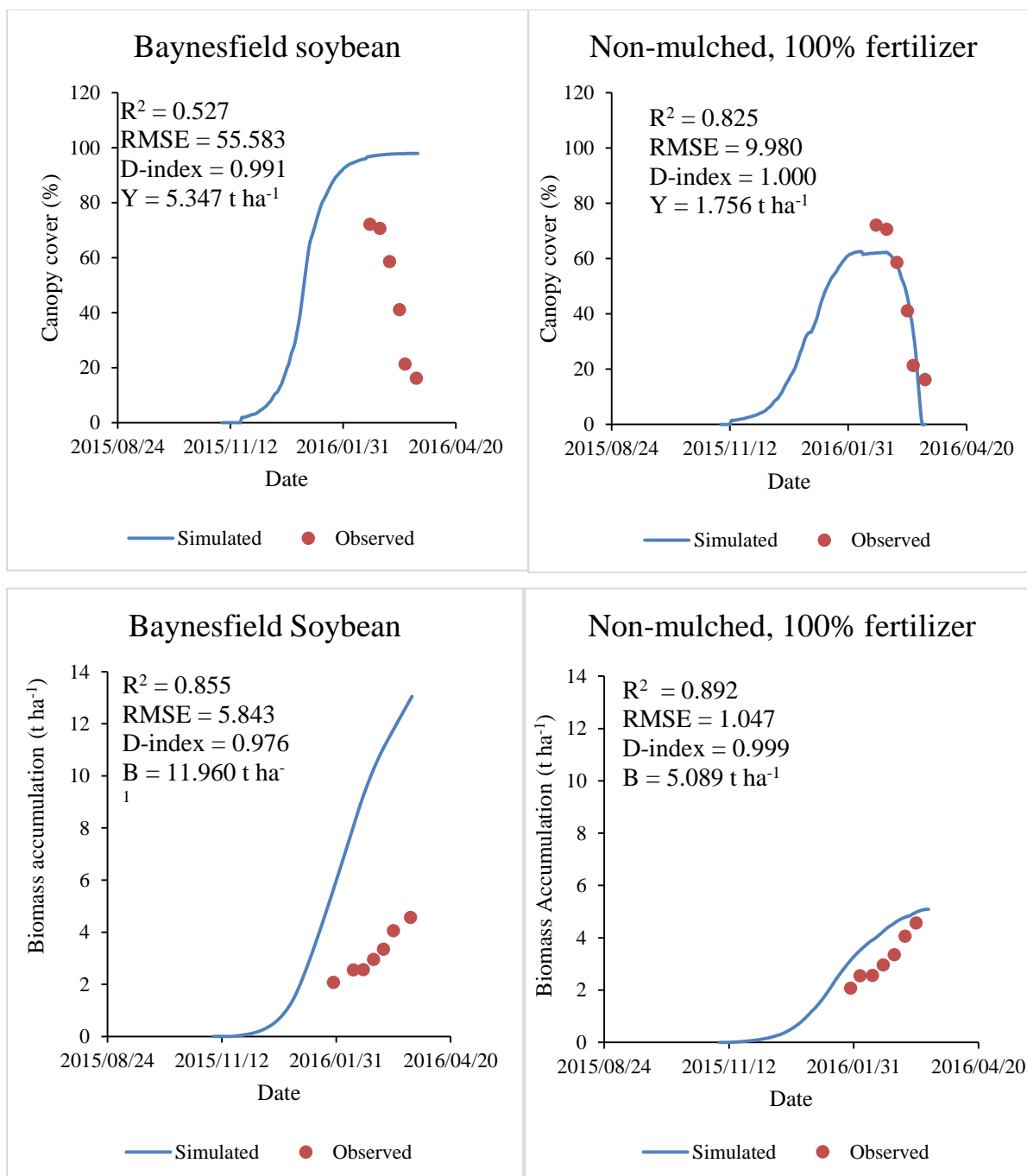


Figure 4.15: Model evaluation by comparing observed and simulated canopy cover and accumulated biomass in AquaCrop (soybean was planted on the 6th November 2015 and harvested on the 29th March 2016)

The simulated final yield (*cf.* **Table 4.8**) was compared to observed yield (*cf.* **Table 4.5**). The model simulated canopy cover well for non-mulched treatments, with R^2 ranging from 0.83 to 0.90 and RMSE within 7 and 10. Biomass was also simulated fairly well in non-mulched treatments, with R^2 ranging from 0.76 to 0.89 and RMSE between 0.84 and 1.0 (*cf.* **Appendix**

10). However, the model simulated biomass poorly under the mulched treatments than compared to the non-mulched plots. The model over-simulated the yield and biomass in the mulched plots because the expected higher yield in the mulched treatments was not observed. Contrary to field observations, the model simulated the highest yield (2.02 t ha^{-1}) under the mulched, full fertilizer treatment. The model does not account for complex interactions between the soil and mulch, as was observed in this case, where mulching is believed to have resulted in poor nodule formation, stunted growth and symptoms of nitrogen deficiency (*cf.* **Section 4.5**). As a result, the model performed better in non-mulched plots than it did in the mulched plots.

Table 4.8: Estimates of crop evapotranspiration and final yield as simulated by AquaCrop

Treatment	Soil water evaporation (mm)	Crop transpiration (mm)	Actual ET (mm)	Biomass (t ha^{-1})	Final yield (t ha^{-1})
Non-mulched, full fertilizer	271.5	218.0	489.5	5.09	1.76
Non-mulched, half fertilizer	277.6	210.1	487.7	4.56	1.37
Non-mulched, zero fertilizer	297.5	184.6	482.1	3.51	1.19
Mulched, full fertilizer	165.1	251.0	416.1	5.80	2.02
Mulched, half fertilizer	174.0	233.9	407.9	4.91	1.66
Mulched, zero fertilizer	183.9	214.4	398.3	3.73	1.27

In Baynesfield, a yield of 5.4 t ha^{-1} was simulated by AquaCrop, which compared well with the observed value of 5.28 t ha^{-1} . Kunz *et al.* (2015) successfully used the AquaCrop model to derive regional estimates of, *inter alia*, soybean water use. In the study carried out by Paredes *et al.* (2015), AquaCrop simulated soybean yield and biomass well. This was believed to be the result of the appropriate calibration of the CC curve. However, poor estimates of evapotranspiration were obtained. This was attributed to the AquaCrop model abandoning the FAO56 dual K_c approach (as described by Allen *et al.*, 1998) and not being properly tested through specific and focused studies (Paredes *et al.*, 2015). Mabhaudhi (2012) also reported that the AquaCrop model estimated yield, biomass and canopy cover reasonably well for Bambara groundnut and satisfactory simulations for taro under field conditions were also

achieved. Hadebe (2015) also reported that the model simulated yield, biomass and canopy cover well for sorghum.

Crop water use (i.e. crop evapotranspiration) simulated by the model was lower in the mulched treatments compared to non-mulched treatments (*cf.* **Table 4.8**). Furthermore, soil water evaporation contributed more to crop evapotranspiration than transpiration in the non-mulched plots. Therefore, the mulch layer reduced soil water evaporation as anticipated. This was because the soil surface was covered and thus, less energy was available to evaporate water from the soil surface. However, AquaCrop does not account for interception loss and the evaporation of intercepted water vapour. In Baynesfield, soybean's water use was measured by Mengistu *et al.* (2014) as 469 mm (based on seasonal rainfall of 644.6 mm), while AquaCrop simulated 423 mm (based on seasonal rainfall of 533.1 mm), which was satisfactory.

4.7.2 SWB model

As mentioned previously (*cf.* **Section 2.4.2**), the SWB model does not account for mulching or varying soil fertility levels. Hence, the SWB model was used to simulate crop yield and water use for the non-mulched, full fertilizer treatment, which was then validated against observed data. SWB simulated higher crop water use of 521.5 mm, compared to 489.5 mm simulated by AquaCrop (*cf.* **Table 4.9**). However, both models simulated higher soil water evaporation rates when compared to transpiration under the control treatment. In AquaCrop, the amount of soil water evaporation is affected by ground cover (Raes *et al.*, 2012). As can be seen in **Figure 4.15** in **Section 4.7.1**, the measured canopy cover peaked at 72%. Therefore, a relatively large portion of the soil surface was not shaded, which resulted in greater soil evaporation. However, under mulched treatments, the model reduces soil water evaporation, depending on the mulch type and the portion of soil surface covered by mulch. In the SWB model, the partitioning between transpiration and evaporation is affected by the amount of energy reaching the crop canopy and the soil surface, as well as the resistance to water movement, such as atmospheric evaporative demand (Annandale *et al.*, 1999). Therefore, the higher rate of soil evaporation rather than transpiration simulated by the SWB model may also be attributed to higher radiation energy reaching the soil surface as a result of the observed sparse canopy cover.

Table 4.9: Crop water use as simulated by the SWB model for the full fertilizer, non-mulched treatment

Soil water balance (mm)	Value
Crop transpiration	200.4
Soil water evaporation	321.1
Crop evapotranspiration	521.5

Furthermore, SWB can simulate crop parameters such as leaf area index (*cf.* **Figure 4.16**), biomass accumulation and final yield (*cf.* **Figure 4.17**), which was then compared to observed data in order to evaluate model performance. Although the model over-simulated leaf area index and biomass accumulation, the final yield was simulated well. Model performance was adequate, with an R^2 of 0.87 for leaf area index and 0.94 for the biomass.

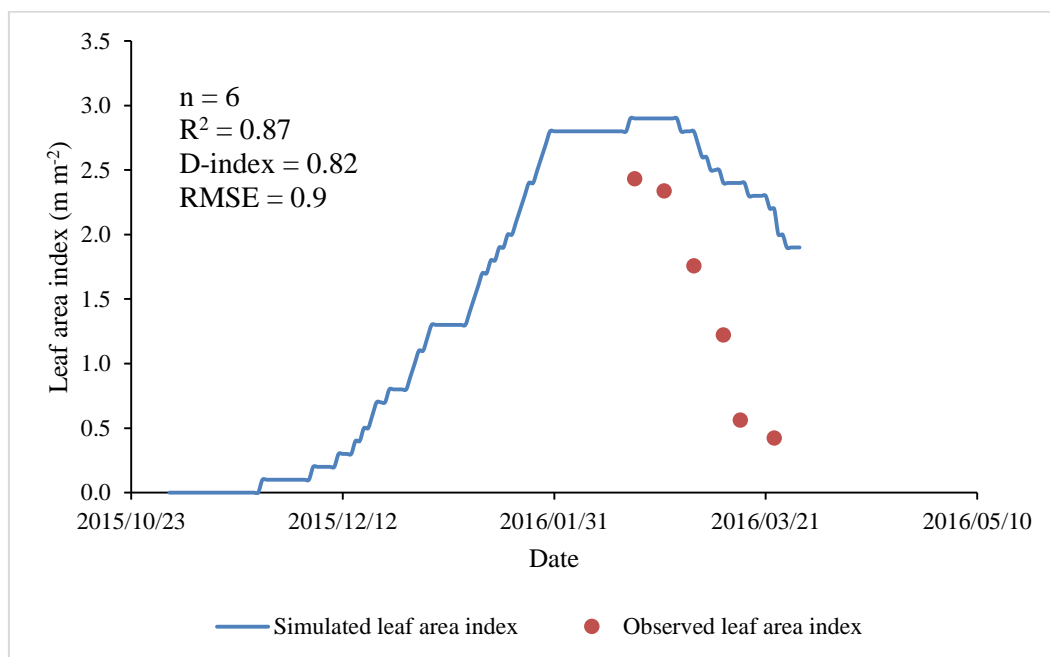


Figure 4.16: Leaf area index for the full fertilizer, non-mulched treatment as simulated by the SWB model

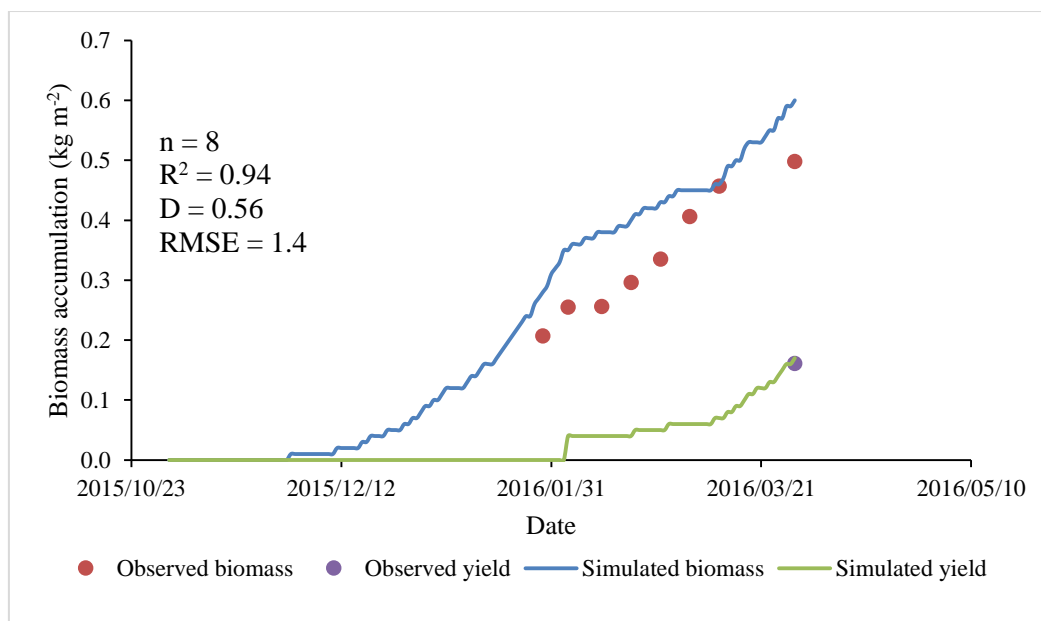


Figure 4.17: Biomass accumulation and final yield for the full fertilizer, non-mulched treatment as simulated by the SWB model

The SWB model simulated the final yield as 1.60 t ha^{-1} (or 0.16 kg m^{-2}) while AquaCrop simulated 1.76 t ha^{-1} for the non-mulched, full fertilizer treatment. Therefore, the SWB provided a closer estimate of the actual yield (i.e. 1.61 t ha^{-1}) than AquaCrop. The yield simulation by AquaCrop (1.76 t ha^{-1}) was higher than the observed yield (1.61 t ha^{-1}). This may be attributed to higher transpiration rates that were simulated by AquaCrop (218 mm; *cf.* **Table 4.8**) when compared to transpiration estimated by the SWB model (200.4 mm; *cf.* **Table 4.9**). A higher transpiration rate infers a higher crop yield.

4.7.3 Water use efficiency

Crop yield and water use was simulated by AquaCrop and the SWB model, from which water use efficiency was calculated. Water use efficiency was calculated as seed yield (WUE_s) per unit of water used by the crop (*cf.* **Table 4.10**). Crop water use could not be estimated on site as runoff was not measured (due to budget and time constraints) and could not be assumed to be negligible. Therefore, no observed values of water use efficiency could be made.

Table 4.10: Water use efficiency derived from AquaCrop model simulations

Mulching treatment	Fertilizer level	Crop yield (kg ha⁻¹)	Water use (m³)	Water use efficiency (kg m⁻³)
Non-mulched	100	1756	4895	0.359
Non-mulched	50	1566	4877	0.321
Non-mulched	0	1185	4821	0.246
Mulched	100	2017	4161	0.485
Mulched	50	1664	4079	0.408
Mulched	0	1267	3983	0.318

WUE_s was highest for the mulched, full fertilizer treatment. The model simulated higher WUE_s under mulched treatments when compared to non-mulched treatments, which was the expected response since mulching reduces soil water evaporation. The simulation implies that mulching can improve WUE_s provided that nitrogen remains available for crop uptake.

The water use efficiency derived from the SWB model simulations was compared to that derived from AquaCrop for the non-mulched, full fertilizer treatment (*cf.* **Table 4.11**). The models provided relatively similar results, with the SWB simulating lower WUE_s. The non-mulched, full fertilizer treatment was then compared to AquaCrop simulations reported by Mengistu *et al.* (2014) for the 2012/13 season at Baynesfield.

Table 4.11: Comparison of water use efficiency derived from the AquaCrop and SWB model

Model	Yield (kg ha⁻¹)	Water use (m³)	Water use efficiency (kg m⁻³)
SWB	1600	5215	0.307
AquaCrop	1756	4895	0.359

The rainfall from the beginning of November to end of March was recorded as 425 mm at Baynesfield, compared to 533 mm recorded in Swayimane in the 2015/16 season. To allow comparison, the seed oil content of the non-mulched, full fertilized treatment was assumed as 18%, which is slightly higher than 17.4% obtained in this study. According to **Table 4.12**, the WUE_s obtained in Swayimane (representing a smallholder farmer) was 72% less than that for Baynesfield (representing a commercial farm). The findings of this study highlight a substantial difference in WUEs experienced by smallholder and commercial farmers. However, implementing appropriate agronomic practices can improve yield, and hence WUE, whereas

poor management can have adverse impacts on yield, as observed in this study where mulching expectantly reduced yield.

Table 4.12: Comparison of yield, water use and water use efficiency between commercial and smallholder farmer environments as simulated by the AquaCrop model

Variable	Baynesfield	Swayimane
Yield (t ha ⁻¹)	5.4	1.76
Water use (m ³)	4230	4895
WUE _S (kg m ⁻³)	1.277	0.359
Biofuel yield (L ha ⁻¹)	1003.7	326.4
WUE _B (L m ⁻³)	0.237	0.067

The soil water balance parameters that were simulated by both the AquaCrop and SWB are fairly similar (*cf.* **Table 4.13**). However, the SWB model simulation of ET was 6% higher than was simulated by AquaCrop. Drainage simulated by the models are similar, while the AquaCrop model simulated higher surface runoff than the SWB model. A limitation of the AquaCrop model is the inability to simulate interception. Thus, the AquaCrop model may over-estimate ET since it does not account for canopy interception losses. This is one of the reasons which may have caused the discrepancy in change in soil water content (ΔS) simulated by both models. The SWB model simulated the soil profile as being drier at the end of the season than at the beginning (*cf.* **Figure 4.18** below). In comparison, the AquaCrop model simulated similar profile water contents at the beginning and end of the season. However, the change in soil water content simulated by AquaCrop was 83% less than that simulated by the SWB model, which is significant but difficult to explain.

Table 4.13: Comparison of SWB and AquaCrop soil water balance parameters

Soil water balance parameter (mm)	SWB	AquaCrop
ET	521.5	489.5
Drainage	16.0	16.1
Runoff	23.61	37.0
Interception	29.5	-
ΔS	-57.6	-9.6

Note: - indicates values that could not be estimated; ΔS = change in soil water content

In order to assess model accuracy in the simulation of soil water content, the estimated soil water content derived from measurements of soil water tension using the soil Watermark

sensors, was compared to model simulations of profile soil water content. In order to estimate soil profile water content for each treatment, each sensor in the field plots (i.e. at 0.15 m, 0.3 m and 0.6 m soil depths) represented a total of 0.6 m of the soil profile. To represent the bottom 0.4 m soil depth, the sensors in the drainage pits (i.e. at the 0.8 m and 1 m soil depths) were used. Therefore, the profile water content was estimated to the 1 m depth, with each sensor representing approximately 0.2 m of the soil profile. In the mulched, 50% fertilizer treatment, the 0.15 m Watermark sensor was disregarded as it was occasionally dysfunctional. Therefore, in that instance, the sensor at 0.3 m represented the top 0.4 m soil profile. The profile water content for the non-mulched, full fertilizer treatment is presented in **Figure 4.18**, while that of the other treatments are presented in **Appendix 11**. Both the AquaCrop and SWB models simulated similar profile water content at the initial stage. When compared to water content estimated by Watermark sensors, both models simulated similar trends. However, AquaCrop over-simulated, while SWB under-simulated the profile water content.

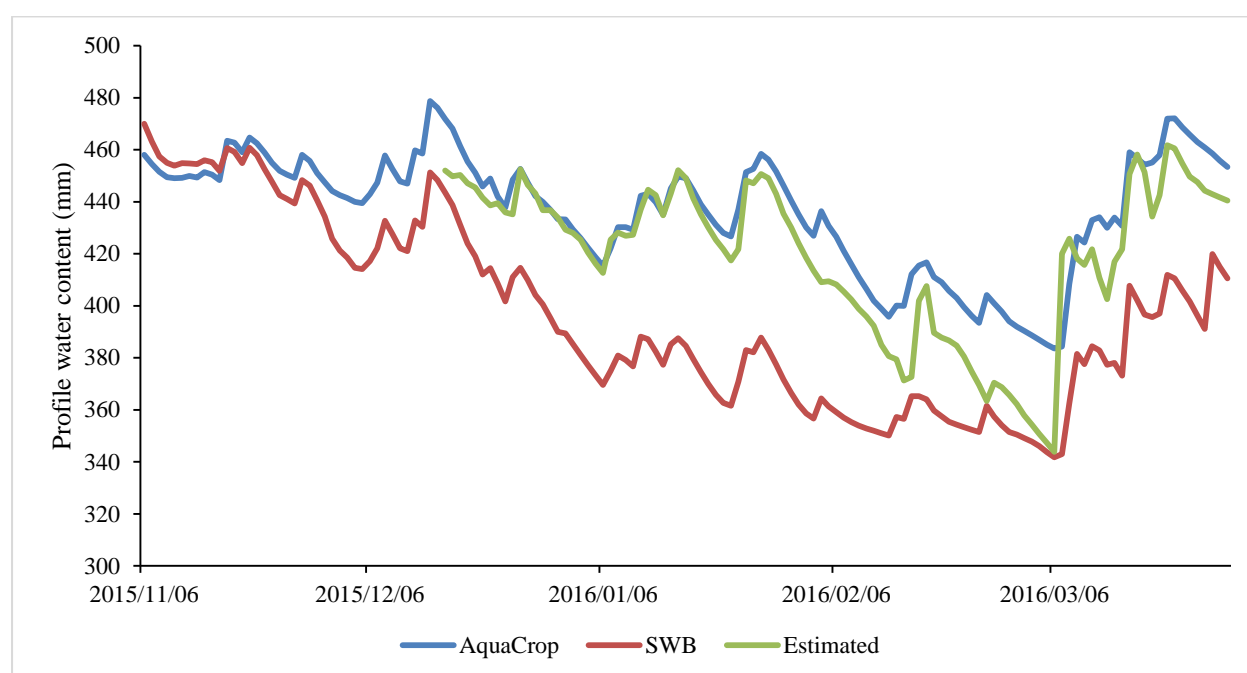


Figure 4.18: The comparison of profile water content between estimated and simulated values derived using the AquaCrop and SWB models for the non-mulched, full fertilizer treatment

4.7.4 Biofuel use efficiency

Biodiesel use efficiency was calculated as the amount of biodiesel produced (L) per unit of water used (m^3). The simulated crop yield by AquaCrop was used, together with the measured seed oil content (as reported in **Table 4.7** in **Section 4.6**). Biofuel use efficiency (WUE_B) was highest under the non-mulched, full fertilizer treatment (*cf.* **Table 4.14**).

Table 4.14: Biofuel yield derived from crop yield as estimated by AquaCrop and measured seed oil content, then normalised by crop water use to obtain biofuel use efficiency

Mulching treatment	Fertilizer level	Theoretical biofuel yield (L ha ⁻¹)	Biofuel use efficiency (L m ⁻³)
Non-mulched	100	315.5	0.064
Non-mulched	50	281.4	0.058
Non-mulched	0	204.3	0.042
Mulched	100	427.0	0.103
Mulched	50	360.8	0.088
Mulched	0	232.9	0.058

According to AquaCrop, the mulched, full fertilizer treatment produced the highest biofuel use efficiency. However, as shown in **Table 4.7** in **Section 4.6**, the highest biofuel use efficiency was produced by the non-mulched, full fertilizer treatment. This discrepancy can be attributed to the model simulating higher crop yields under the mulched treatments, contrary to field observations, as mentioned previously in **Section 4.7.1**. The estimation of biofuel use efficiency derived from AquaCrop for the non-mulched, full fertilizer treatment was compared to the estimation made by the SWB model. AquaCrop estimated biofuel efficiency at 14% higher than SWB (*cf.* **Table 4.15**).

Table 4.15: The comparison of the estimation of biodiesel use efficiency derived from the SWB and AquaCrop models

Model	Theoretical biodiesel yield (L ha ⁻¹)	Biodiesel use efficiency (L m ⁻³)
AquaCrop	315.5	0.064
SWB	287.5	0.055

4.7.5 Crop coefficients

Crop coefficients (K_c) were calculated based on crop water use and yield derived from AquaCrop using **Equation 3.3** in **Section 3.6.2** and are summarized in **Table 4.16**. However, the K_c 's presented in this study were not obtained under stress-free conditions as recommended by FAO. Hence, they may not be easily transferable or applicable to other sites.

Table 4.16: Crop coefficients derived from AquaCrop

Mulch treatment	Fertilizer level (%)	K _C initial	K _C mid	K _C peak	K _C end
Non-mulched	100	0.53	0.80	0.91	0.40
Non-mulched	50	0.65	0.78	0.90	0.43
Non-mulched	0	0.66	0.78	0.90	0.42
Mulched	100	0.48	0.70	0.80	0.41
Mulched	50	0.42	0.57	0.76	0.42
Mulched	0	0.42	0.55	0.76	0.39

During the initial crop growth stage, the predominant component of crop evapotranspiration is soil water evaporation. Therefore, the initial K_C value is largely influenced by the frequency and magnitude of wetting events. The initial K_C is expected to approximate 0.4, as this is a typical value for legumes such as soybean according to Allen *et al.* (1998).

The K_C mid and K_C end values for the non-mulched, 100% fertilizer treatment are lower than those reported by Kunz *et al.* (2015) for Baynesfield. This implies that less water was used by the crops in this study compared to the crop water use at Baynesfield. This can be expected since the yield obtained in Baynesfield was higher than the yield obtained in Swayimane. Furthermore, high relative humidity was recorded on site, which may have affected both the evaporative demand (ET_O) and crop water use (ET) and consequently, K_C.

The simulated K_C values derived using output from both models is compared in **Table 4.17**. The models provided similar estimates of K_C, which improves the confidence in model simulations of water use efficiency.

Table 4.17: The comparison of crop coefficients derived from AquaCrop and the SWB model for the non-mulched, fully fertilized treatment

Model	K _C initial	K _C mid	K _C peak	K _C end
AquaCrop	0.53	0.80	0.91	0.40
SWB	0.41	0.81	0.97	0.56

5 CONCLUSIONS

5.1 Summary of Approach

The aim of this study was to estimate the water use and yield of soybean under rainfed conditions and to assess the impact of mulching and soil fertility on crop yield using the AquaCrop model. The SWB model was used to compare crop water use and yield simulated by AquaCrop for the non-mulched, fully fertilized treatment. A soybean field trial was established in Swayimane to parameterize AquaCrop and SWB models. Both models were validated using observed field data, namely leaf area index, biomass accumulation, final yield and total biomass. The final crop yield and biomass was estimated from six plants that were representative of each treatment. The impact of mulching and soil fertility on crop yield was then assessed.

In order to simplify the study within the allocated time and financial resources, not all components of the soil water equation were measured in the field (e.g. runoff). Therefore, it was deemed more feasible to simulate crop water use using the AquaCrop and SWB models. However, the latter model was only used for the control treatment as the model cannot account for neither mulching, nor varying soil fertility levels. Crop water use (ET) was simulated using both models via the soil water balance equation. Crop coefficients were derived from model simulations, under non-standard conditions. Water use efficiency and biofuel use efficiency were estimated from the crop yield and biofuel yield, respectively. The latter is sensitive to the seed oil content which was measured in a laboratory.

Soil water content was measured using Watermark sensors and calibrated using regression curves of gravimetric water content and corresponding soil matric potential. Drainage was assumed to occur when the soil water content at the bottom of the rooting zone exceeded field capacity. These parameters were compared to model simulations. The impact of mulching on surface soil temperature and soil water content was also evaluated.

An automatic weather station was installed to obtain climatic data and to calculate reference crop evapotranspiration (ET_0). However, since the data collection began after planting, the Bruyns Hill weather station situated near Wartburg was used to extend the record to the beginning of November 2015. This station was also used to patch erroneous maximum relative humidity readings as well as to validate the weather data recorded at Swayimane. Soil texture was determined by the Soil Analytical Service Laboratory. Soil saturation and field capacity

were estimated using the controlled outflow method in the UKZN soils laboratory. Due to the failure of the high-pressure compressor, permanent wilting point was estimated by the SPAW model. These soil parameters were then used to derive soil water retention curves using two different approaches.

5.2 Summary of Findings

The AquaCrop model simulated yield and biomass well in the non-mulched treatments. However, model simulations were poor in mulched treatments because the model does not account for the complex interactions between the effects of mulching on N immobilization and poor nodule formation. According to the model, the mulched treatments should produce the highest yield, as is expected. The SWB model produced similar estimates of crop water use and yield as those simulated by AquaCrop for the non-mulched, fully fertilized treatment. This improved the confidence of simulations made by AquaCrop for the other treatments.

As expected, observed crop yield was higher under increasing soil fertility. Hence, water use efficiency was also improved by higher levels of soil fertility. Simulated water use of soybean was higher under non-mulched treatments compared to mulched treatments. Under mulched treatments, a greater portion of crop evapotranspiration occurred as transpiration rather than soil water evaporation. This equated to higher yields and thus, greater water use efficiency.

However, mulching resulted in lower yields than non-mulched treatments. This may have been caused by poor nodule formation in the crop roots. The impact of poor nodulation may have been worse in the mulched plots. This is believed to be a result of nitrogen (N) competition between the crop and the soil microbes that were responsible for decomposing the straw mulch. This resulted in apparent N deficiency symptoms (i.e. yellowing and stunted growth of mature soybean leaves).

Mulching was shown to reduce soil surface temperature. Soil water content was higher under the mulching, as was expected. Additionally, fluctuations in water content were less than soil water fluctuations in non-mulched treatments.

In conclusion, optimum soil fertility and mulching should improve crop yield. However, when growing soybean in a soil with a poor *Bradyrhizobia japonicum* bacteria population, a starter application of N should be applied and the seed inoculated with the *Bradyrhizobia japonicum* bacteria. Only then should the positive impacts of mulching be realized.

5.3 Recommendations for Future Research

From the findings of the study, the following recommendations for future research are made:

- Soybean inoculation is essential, especially when mulching is practiced. Straw mulch has a high C:N ratio, which means soil microbes require nitrogen to decompose the carbon from the decaying mulch. This results in competition for nitrogen with the crop and may lead to symptoms of nitrogen deficiency when no residual N is present in the soil (i.e. stunted growth and yellowing of older leaves). Subsequently, a yield reduction can occur as observed in this study. Seed inoculation (or a starter dose of N application) may ameliorate the adverse impacts of decaying straw mulch on the yield. Therefore, it is recommended that the experiment be repeated with the use of inoculant.
- Testing of plant tissue in conjunction with soil tests would prove beneficial to ascertain actual nutrient uptake by the plant. It may be inaccurate to assume that loss of nutrients from the soil is solely attributed to plant uptake. Furthermore, the source of any additional soil nutrients that was applied through fertilizer (as observed with P in this study) might easily be traced when plant tissue is tested for nutrients. One might assume that nutrients were remobilized from plants, when they may have been leached from residue. Testing of plant tissue during crop growth can also reveal nutrient deficiencies, which might be ameliorated to reduce yield loss.
- In the case of soybean, the active nodule number should be counted during the growing season. This can reveal whether or not nodulation is sufficient. This can prevent loss of soybean yield caused by poor nodulation, as the capacity of the plant to fix nitrogen is limited under poor nodulation.
- The soil water characteristics calculator (or SPAW) model was efficient in estimating soil water characteristics, considering the few input parameters required (i.e. a bare minimum of soil texture is required to run the model). However, soil organic matter, salinity, gravel and soil compaction can be provided as model input to help improve the accuracy of estimations. Overall, the model provided reliable estimates and can be used in studies where actual laboratory measurements of soil water retention characteristics cannot be carried out. The only parameter with a low R^2 value was the bulk density. The model also

saves time compared to laboratory measurements. However, actual measurements are indispensable as they account for actual field conditions.

- A simplistic approach was undertaken in this study to estimate volumetric soil water content using gravimetric samples. This approach produced more accurate simulations than the widely-applied van Genuchten (1980) equation, which is also more complex and time consuming. However, it is important to note that since the regression curves were derived from the gravimetric points, it stands to reason that they should correlate better with the regression curve. However, a limitation of the regression curves is that the equations are valid only for the range of soil matric potentials from which they were derived. Obtaining more gravimetric samples during the growing season can improve the accuracy of volumetric soil water content estimation.
- The use of another type of soil water probe that provides direct measurement of soil water content (without the need for any calibration) would be beneficial. This probe (e.g. CS650 probe from Campbell Scientific Africa) could be installed adjacent to the Watermark sensor at the same depth. The continuous readings from both sensors would provide a good calibration dataset.
- AquaCrop should be modified in order to account for interception loss as it significantly over-estimated soil water content when compared to the SWB model.
- The change in soil water content simulated by AquaCrop was 83% less than that simulated by the SWB model. This difference should be investigated further in order to better understand the causes of such a difference.
- The accuracy of using a default base temperature of 5 °C by the AquaCrop should be investigated as this value is different to the value used by several authors who used 10 °C.

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7 APPENDICES

Appendix 1: Climatic and agronomic requirements for optimal growth of biofuel feedstocks
(adapted from DAFF, 2010a; DAFF, 2010b; FAO, 2013b; Kunz *et al.*, 2015)

Crop	Crop Management	TSR (mm)	MDT (°C)
Soybean	Needs 10-20 kg ha ⁻¹ N: 15-30 kg ha ⁻¹ P: 25-60 kg ha ⁻¹ K nutrients		
	Weed control in early stages of growth	450-900	20-30
	Crop density: 25-40 plants m ⁻²		
Canola	Needs 180-200 kg ha ⁻¹ N: 15-30 kg ha ⁻¹ P: 20-40 kg ha ⁻¹ K		
	Herbicide use essential	Dryland: 200-450	10-30
	Weed control in early stages of growth	Irrigated: 600-700	
Grain sorghum	Crop density: 20-40 plants m ⁻² (dryland)		
	50-70 plants m ⁻² (irrigated)		
	Timely application of fertilizer	450-650	20-25
	Needs 180 kg ha ⁻¹ N: 20-45 kg ha ⁻¹ P: 35-80 kg ha ⁻¹		
	Dust seeds with herbicide before planting		
	Crop density: 65-100 plants m ⁻²		

Note: TSR = total seasonal rainfall, MDT = mean daily temperature.

Appendix 2: Soil texture at Swayimane as measured by the Soil Analytical Service Laboratory at Cedara College of Agriculture from samples derived from drainage pit 1

Soil Depth	Coarse Silt & Sand			
(m)	Clay %	Fine Silt %	%	Texture Class
		(0.002 - 0.02		
	(< 0.002 mm)	mm)	(0.02 - 2 mm)	
0.2	36	15	49	Sandy Clay
0.4	41	11	48	Sandy Clay
0.6	47	7	46	Sandy Clay
0.8	56	6	38	Clay
1.0	54	6	40	Clay

Appendix 3: Procedure followed using the controlled outflow method to obtain soil water retention parameters

The soil water retention values were obtained using the controlled outflow method. A brief description of the method is given here. For more detail, the reader is referred to Lorentz *et al.* (2001; 2004). The controlled outflow pressure method (**Figure 7.1**) was used to estimate the soil water retention parameters by observing the amount of water (mL) released in a certain amount of time at a given pressure. Before any measurements were made, the soil samples were saturated in deionized water for a period of at least 24 hours. From there, the samples were moved to the low-pressure chambers. Each chamber was attached to a burette from which the drainage rate over time was monitored. A certain pressure was then applied to the chamber containing the soil sample. Once the burette reading had increased by 2-3 mL, the stop cock of the burette was closed in order to record the time taken as well as the applied and equilibrium pressures. The pressure was then increased at set intervals, with the process guided by a spreadsheet which gave the suggested increments in gauge pressure (cm). The spreadsheet was also used to convert the transducer pressure (in mV) to gauge pressure (in cm).

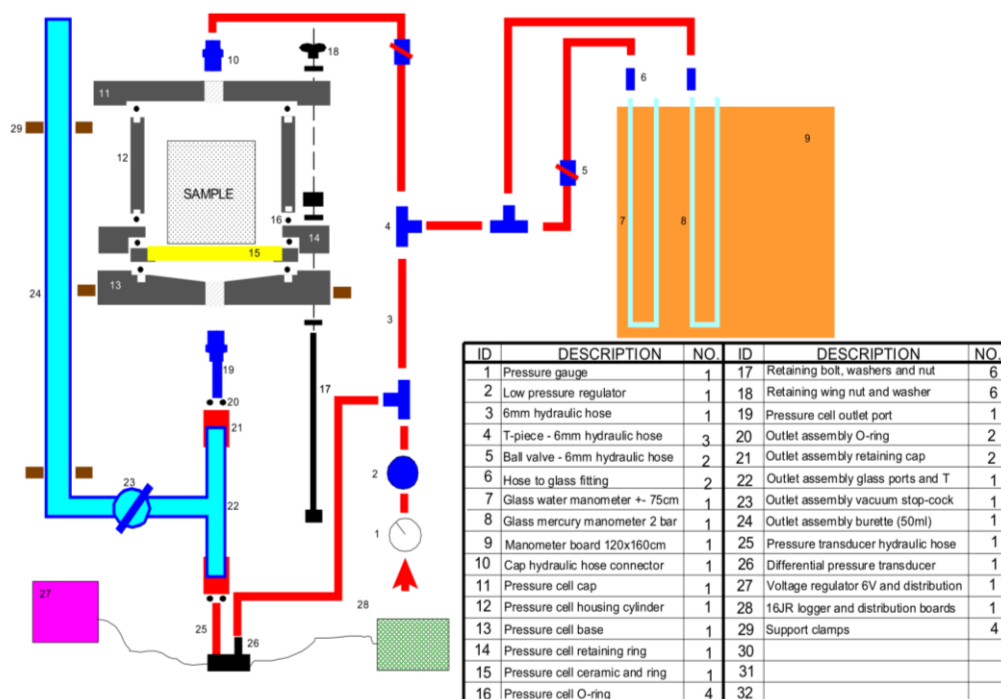


Figure 7.1: Diagram of the structure of the controlled outflow method (source Lorentz *et al.*, 2001)

The pressure applied by the chambers ranges from 0 to -100 kPa and was supplied using a low pressure air compressor. At low pressures, the relatively larger (i.e. macro) soil pores are drained of water first (Vermaak, 2000). The samples were then removed from the chambers and weighed to obtain their mass. Thereafter, the samples were placed in an oven at 105 °C for 24 hours to obtain the oven-dry mass. The mass and dimension of each core (without the soil sample) were also measured. From this, the dry bulk density of each soil sample was calculated.

Appendix 4: Conversion of Watermark sensor resistance to matric potential

Watermark sensors measure electrical resistance in k Ω , which is then correlated to soil water tension in kPa, after taking into account the soil temperature (Chard, 2002). Different equations exist to calculate matric potential from sensor resistance. According to Spaans and Baker (1992), resistance decreases as soil temperature increases. Hence, resistance values should be adjusted for temperature increases, which means normalising the measured resistance (R_S) to a reference resistance (R_R) as follows:

$$R_R = R_S \cdot [1 + a \cdot (T_S - T_R)] \quad \text{Equation 7.1}$$

where T_S and T_R is the measured and reference temperature respectively. According to Allen (2000), $a = 0.018$ for $T_R = 24^\circ\text{C}$. Spaans and Baker (1992) reported $a = 0.03$ for $T_R = 25^\circ\text{C}$. Campbell Scientific (CSI, 2013) use a different equation as follows:

$$R_R = R_S / [1 - a \cdot (T_S - T_R)] \quad \text{Equation 7.2}$$

where $a = 0.018$ for $T_R = 21^\circ\text{C}$. The above two equations produce comparable results when the same values are used for a and T_R . The equations reviewed in this study include those developed by the manufacturer, Irrometer Co. (Riverside, California, USA) as well as equations recommended by Thomson and Armstrong (1987), Allen (2000), Shock *et al.* (1998) and Campbell Scientific, Inc. (CSI, 2013).

The original equation developed by Irrometer for their Watermark meter (Model 30-KTCD) was based on the following:

$$P = -(R_S - 0.5) / [0.1759(1 - 0.013 T_S)] \quad \text{Equation 7.3}$$

where P = soil water matric potential in kPa (or J kg⁻¹),

R_S = measured resistance in k Ω , and

T_S = sensor (soil) temperature in $^\circ\text{C}$.

The equation developed by Thomson and Armstrong (1987) was for temperature values ranging from 4 - 38 $^\circ\text{C}$ is as follows:

$$P = -R/[0.01306(1.062(34.21 - T_S + 0.01060T_S^2) - R_S)] \quad \text{Equation 7.4}$$

Allen (2000) developed the following equation for Watermark sensors (Model 200SS) based on calibration data obtained from Irrrometer Co.:

$$P = -20[R_S(1 + 0.018(T_S - 24)) - 0.55] \quad \text{Equation 7.5}$$

The equation is most accurate for $R_S \leq 1 \text{ k}\Omega$ (or $P = -9 \text{ kPa}$ for $T_S = 24^\circ\text{C}$) and is based on a reference temperature of 24°C . At zero resistance, the equation produces positive potentials, which is deemed incorrect. The $0.018 \cdot (T_S - 24)$ term represents a 1.8% shift in resistance reading per $^\circ\text{C}$ change in soil temperature from the 24°C reference. The 1.8% per $^\circ\text{C}$ is equivalent to 1% per $^\circ\text{F}$ (Allen, 2000).

Allen (2000) recommended the equation developed by Shock *et al.* (1998) for resistance values above $1 \text{ k}\Omega$, but $\leq 8 \text{ k}\Omega$:

$$P = -(3.21R_S + 4.093)/(1 - 0.009733R_S - 0.01205T_S) \quad \text{Equation 7.6}$$

However, the above equation was developed using experimental data with P in the range -75 to -10 kPa (at 15 and 25°C). The equation was based on 729 observations with an R^2 value of 0.949. Shock *et al.* (1998) reported that the temperature effects on sensor resistance becomes larger as the soil dries (i.e. as P approaches -75 kPa). In order to illustrate the range in readings, Shock *et al.* (1998) reported a reading of -53 kPa at 15°C for a resistance of $10 \text{ k}\Omega$, which compares favourably with the estimated value of -50 kPa . However, at 25°C , a reading of -71 kPa was obtained, which was different to the estimated value of -60 kPa .

Shock *et al.* (1998) do not recommend the above equation for $P < -80 \text{ kPa}$. For $P < -100 \text{ kPa}$ (i.e. $R_S > 8 \text{ k}\Omega$). Allen (2000) developed the following quadratic equation:

$$P = -2.246 - 5.239R_S(1 + 0.018(T_S - 24)) - 0.06756R_S^2(1 + 0.018(T_S - 24))^2 \quad \text{Equation 7.7}$$

Allen (2000) developed the above equation using least squares regression from the Irrrometer calibration data for the range of -200 to -10 kPa . The equation has a coefficient of determination (R^2) of 0.9996 and a standard error estimate of 1.07 kPa .

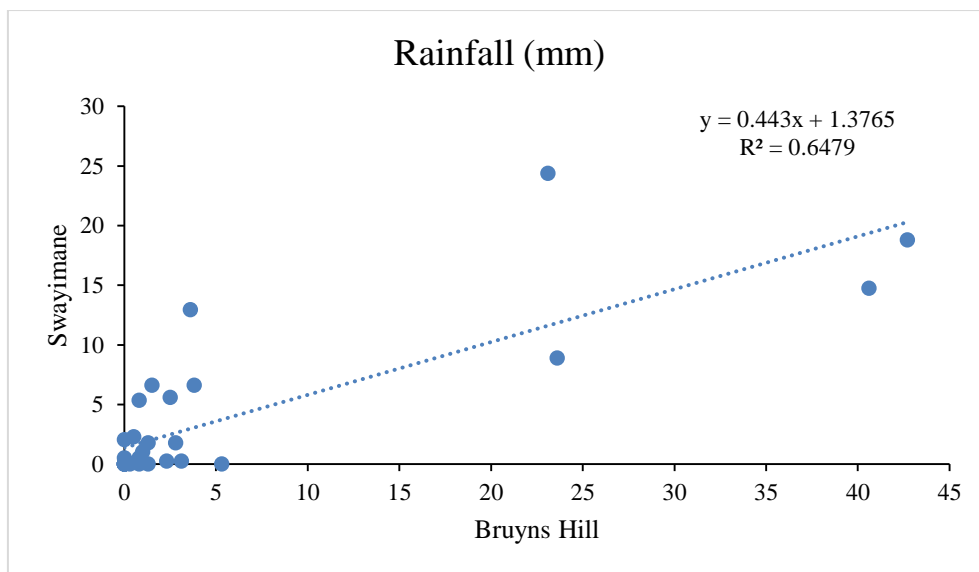
The relationship given by CSI (2013) between resistance (R_S in $k\Omega$) and soil water potential (P in kPa) is as follows:

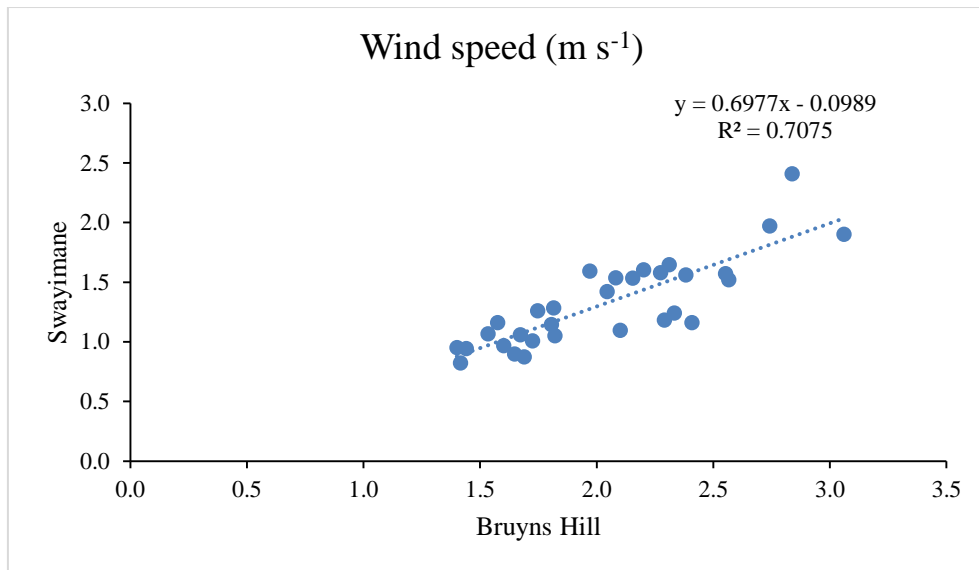
$$P = -(7.407R_S/[1 - 0.018(T_S - 21)] - 3.704) \quad \text{Equation 7.8}$$

The above linear equation adjusts the measured resistance R_S based on soil temperature T_S , i.e. $R_{21} = R_S / [1 - 0.018 \cdot (T_S - 21)]$. Hence, $P = -(7.407 \cdot R_{21} - 3.704)$ (CSI, 2013). The above equation has not been tested beyond measurements of -125 kPa , i.e. $R_S > 17 k\Omega$ (CSI, 2013). CSI (2013) recommend the non-linear Thomson and Armstrong (1987) equation for more precise readings in the -100 to -10 kPa range. It is unclear why CSI (CSI, 2013) use a calibration temperature of 21°C in their equation when Allen (2000) uses 24°C. In this study, **Equation 7.7** was used because it represents the observed range of soil water potential more accurately. Sensor calibration was not done at the beginning of the season as in-field calibration is more suitable than a laboratory calibration using disturbed soils.

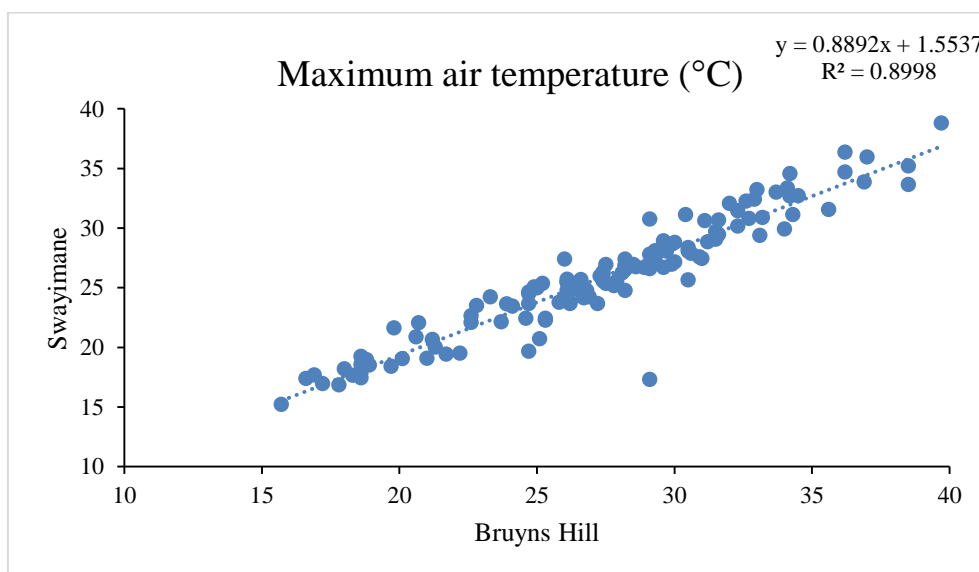
Appendix 5: Correlation of Swayimane and Bruyns Hill data for a complete weather record in Swayimane

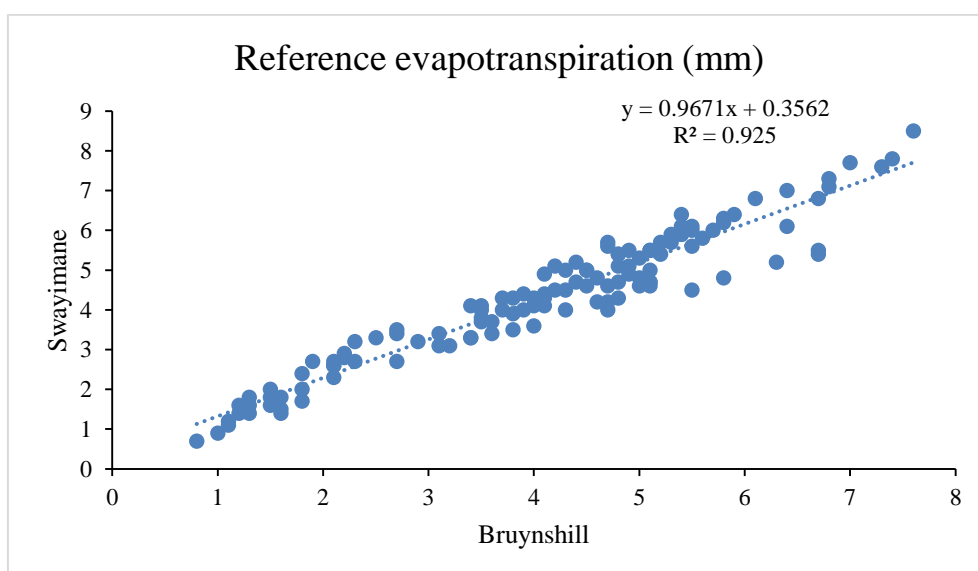
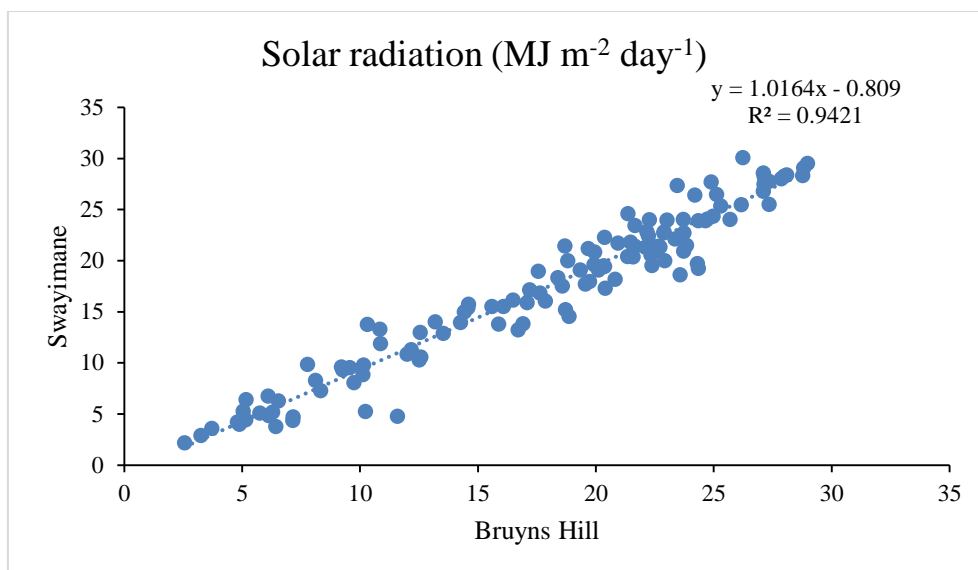
The Bruyns Hill weather station was used to estimate weather data from the 1st November 2015 until the Swayimane weather station started recording data on 27th November 2015. This was achieved by correlating weather data from Bruyns Hill with Swayimane for December 2015. The Swayimane weather data at the beginning of the season was obtained by multiplying the Bruyns Hill data by a correction factor derived from each correlation for rainfall, minimum relative humidity and wind speed.





For other weather variables, data from Bruyns Hill was correlated with that from Swayimane for the period 27th November 2015 to 29th March 2016. This is shown in the graphs below for maximum air temperature, solar radiation and reference crop evapotranspiration.





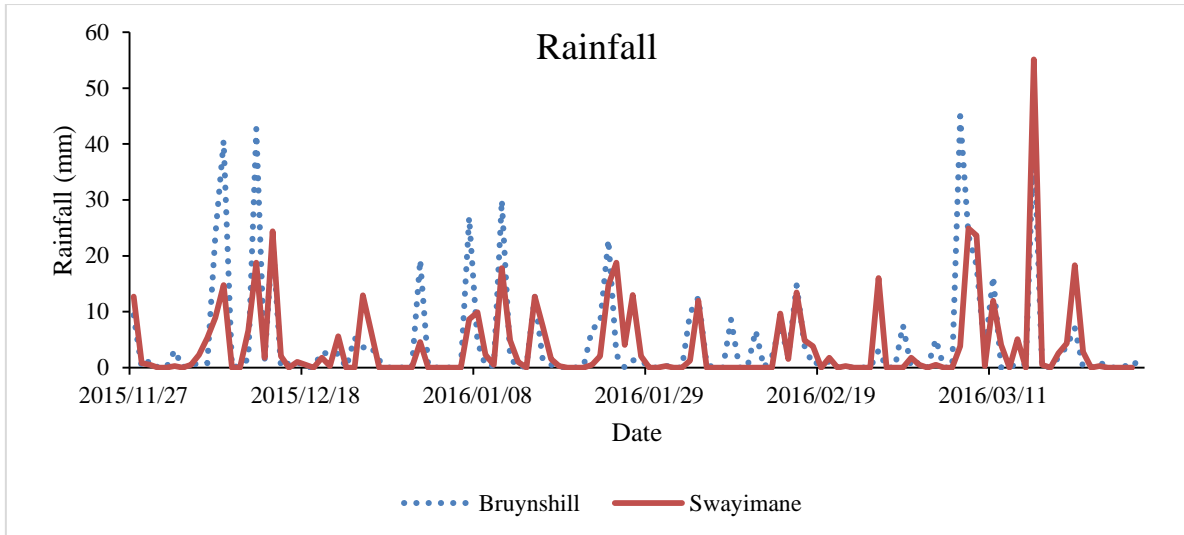
Appendix 6: Observed climate data for Swayimane during the 2015/16 season

Seasonal rainfall data (from beginning of November until end of March) for the previous ten seasons was determined from the historical climate record for Bruyns Hill (*cf.* **Table 7.1**). The average rainfall for all 10 seasons is 551 mm. Hence, the 2015/16 total of 687 mm was well above average and the wettest of all seasons. However, the trial may have been affected by the drought considering the majority of the country experienced drought conditions. In addition, there is insufficient experimental evidence to determine whether or not the trial was actually affected by drought conditions, regardless of the above average rainfall experienced during the growing season.

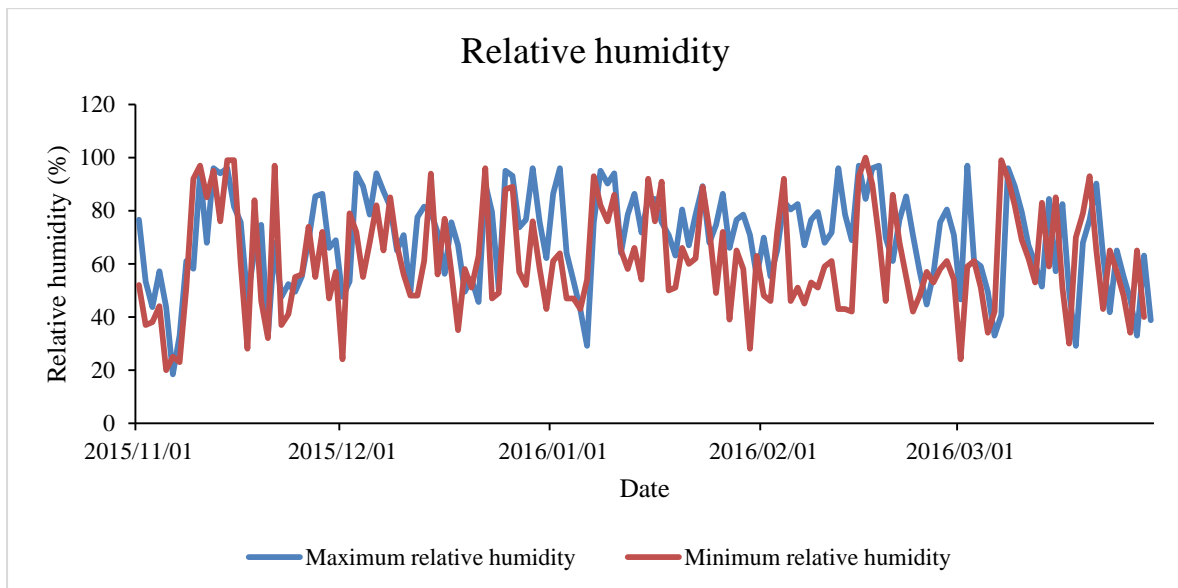
Table 7.1: Seasonal rainfall totals accumulated from 1st November to the end of March for 10 seasons at Bruyns Hill

Season	Rainfall (mm)
2006/07	440
2007/08	509
2008/09	502
2009/10	581
2010/11	587
2011/12	591
2012/13	587
2013/14	525
2014/15	500
2015/16	687

The total rainfall from 1st November 2015 to 29th March 2016 at Swayimane totalled 533.1 mm, which is lower than the 687.1 mm recorded at Bruyns Hill. During the growing season, 9 consecutive days of no rainfall were recorded in Swayimane. The highest daily rainfall event of 55 mm at Swayimane was observed on 16th March 2016, which was then compared to that measured at Bruyns Hill. From the daily rainfall graph presented below, it was concluded that the peak rainfall event is likely to have occurred since a high rainfall event of 47 mm was recorded at Bruyns Hill.

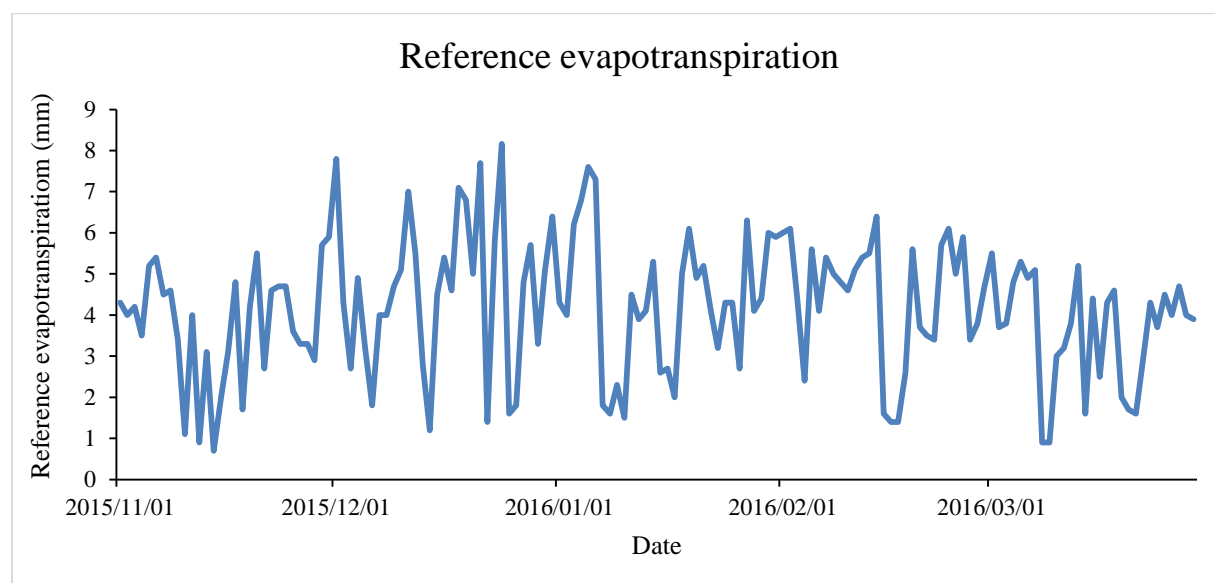


The data logger recorded unrealistically high values of maximum relative humidity (RH_{MAX}) at Swayimane. In order to acquire more representative values, the minimum temperature between Bruyns Hill and Swayimane was correlated. The maximum relative humidity in Bruyns Hill was multiplied by the correlation factor of 0.9794 to obtain more representative RH_{MAX} values for Swayimane. Minimum temperature was used because it has an inverse proportional relationship with RH_{MAX} .

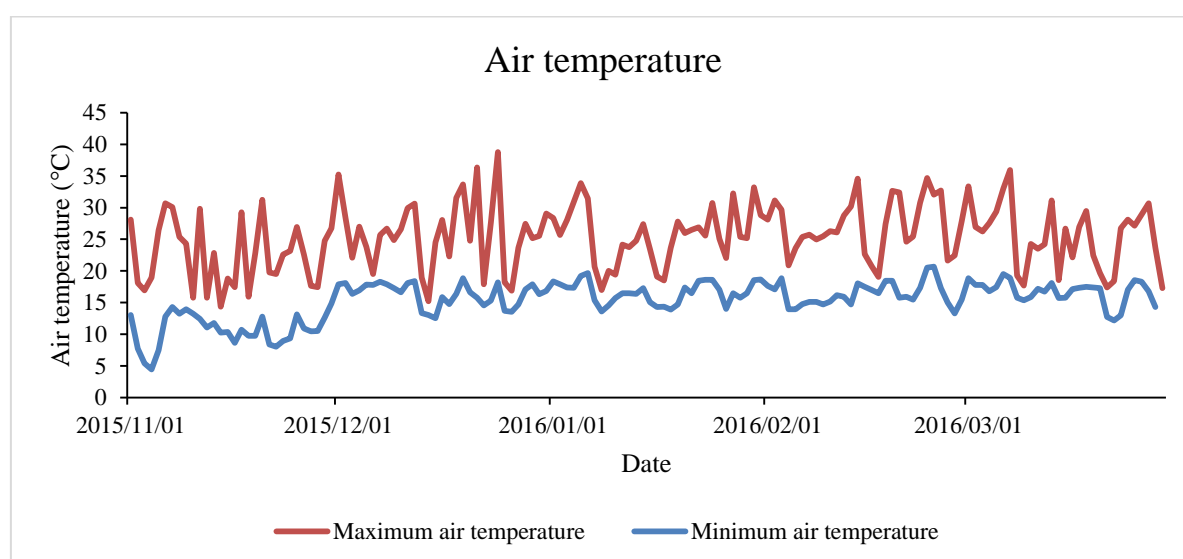


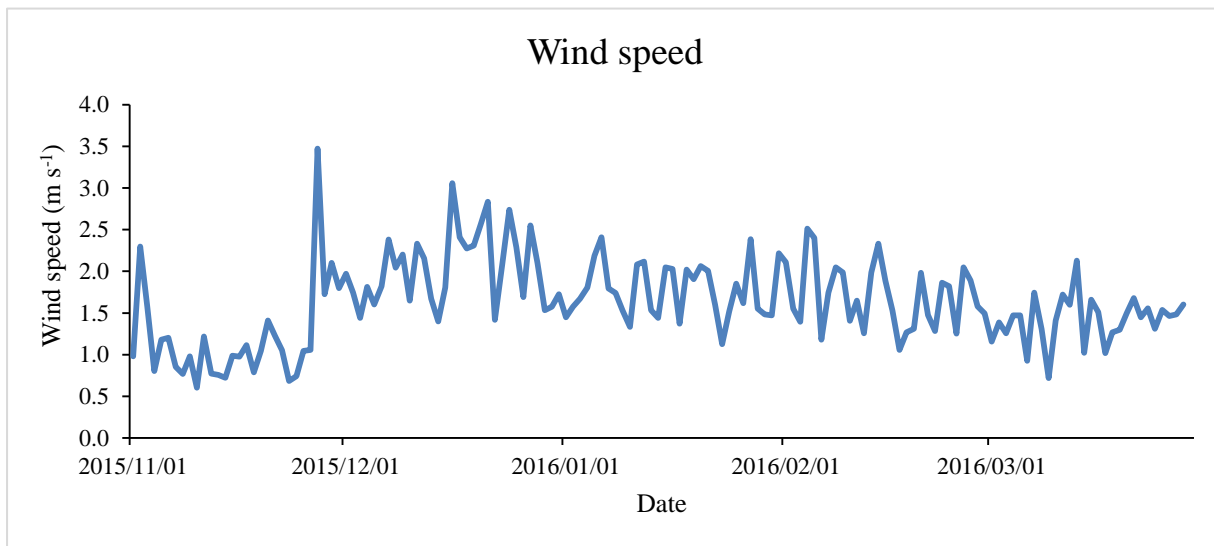
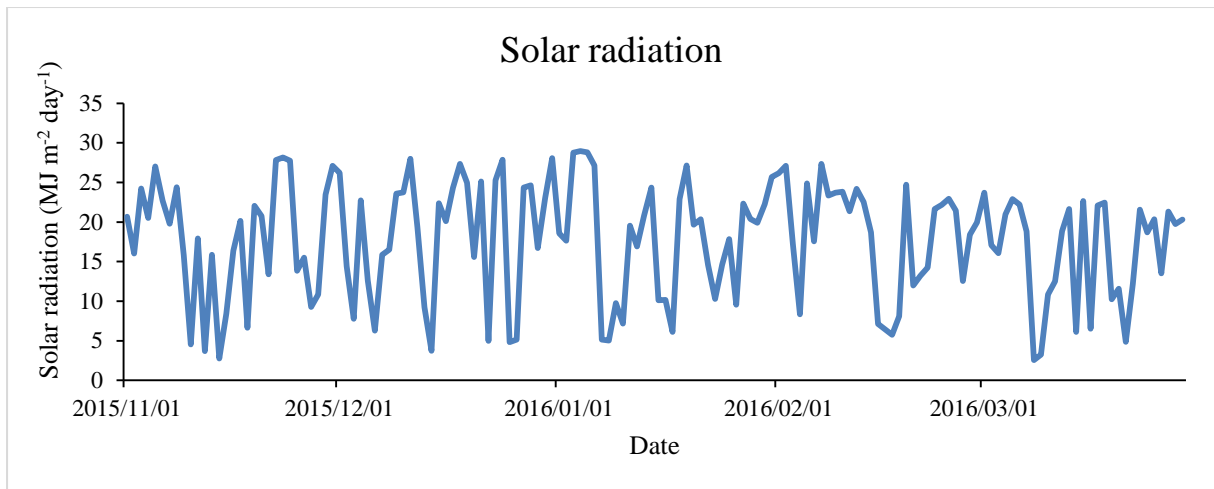
Reference crop evapotranspiration was calculated using the ET_o Calculator (developed by FAO), since the calculations done on site (in the data logger) provided unrealistically low values. The low values are believed to have resulted from the conversion of units from $W\ m^{-2}\ s^{-1}$ to $MJ\ m^{-2}\ day^{-1}$. Daily values were then accumulated manually from the corrected hourly data, which yielded more realistic values. The input required by the ET_o Calculator includes

daily maximum and minimum temperatures, minimum and maximum relative humidity, wind speed and solar radiation. The highest ET_0 value of 8.5 mm was estimated on the 24th of December 2015 (*cf.* **Table 4.2** in **Section 4.1**). This peak ET_0 was higher than the 7.6 mm measured at Bruyns Hill. The Swayimane ET_0 dataset was then correlated against Bruyns Hill in order to determine an appropriate adjustment factor. As a result, the peak ET_0 was adjusted to 8.2 mm. The accumulated ET_0 from 1st November 2015 to 29th March 2016 was estimated as 624.2 mm, whereas the accumulated ET_0 in Bruyns Hill amounted to 590.9 mm.

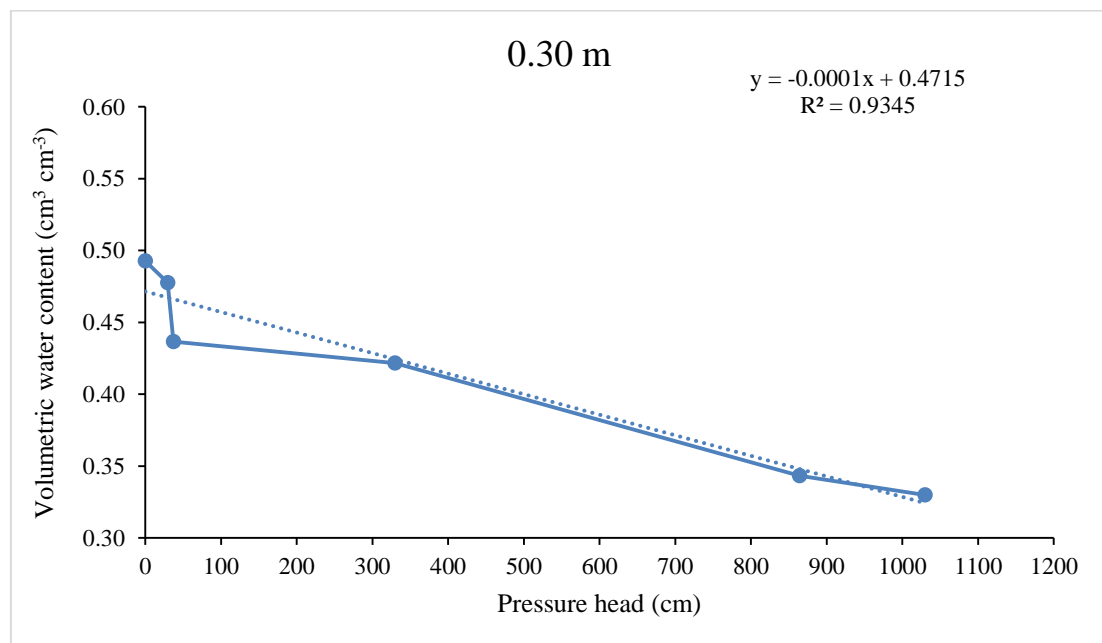
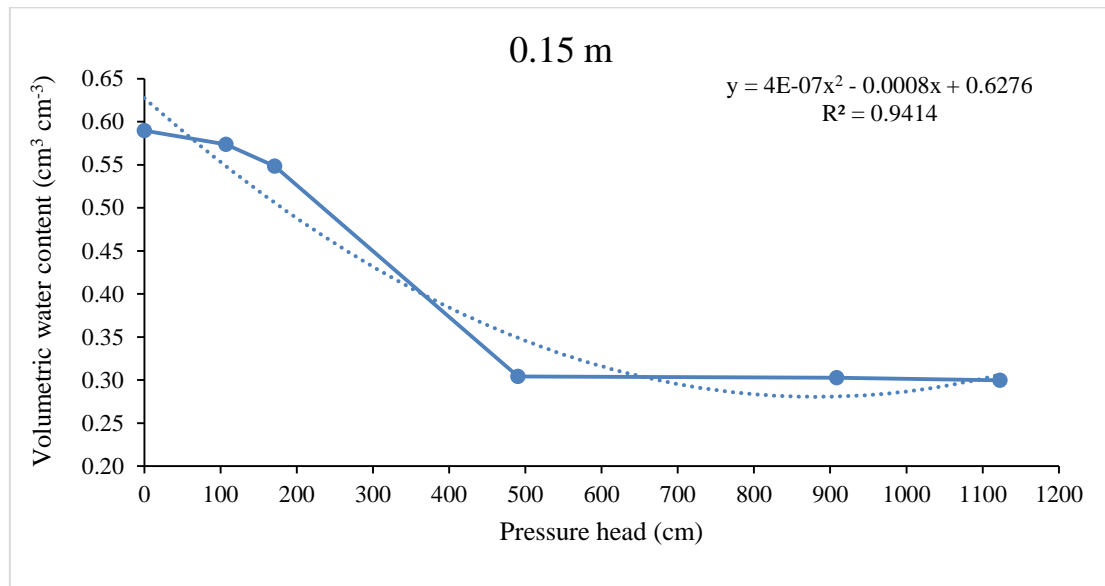


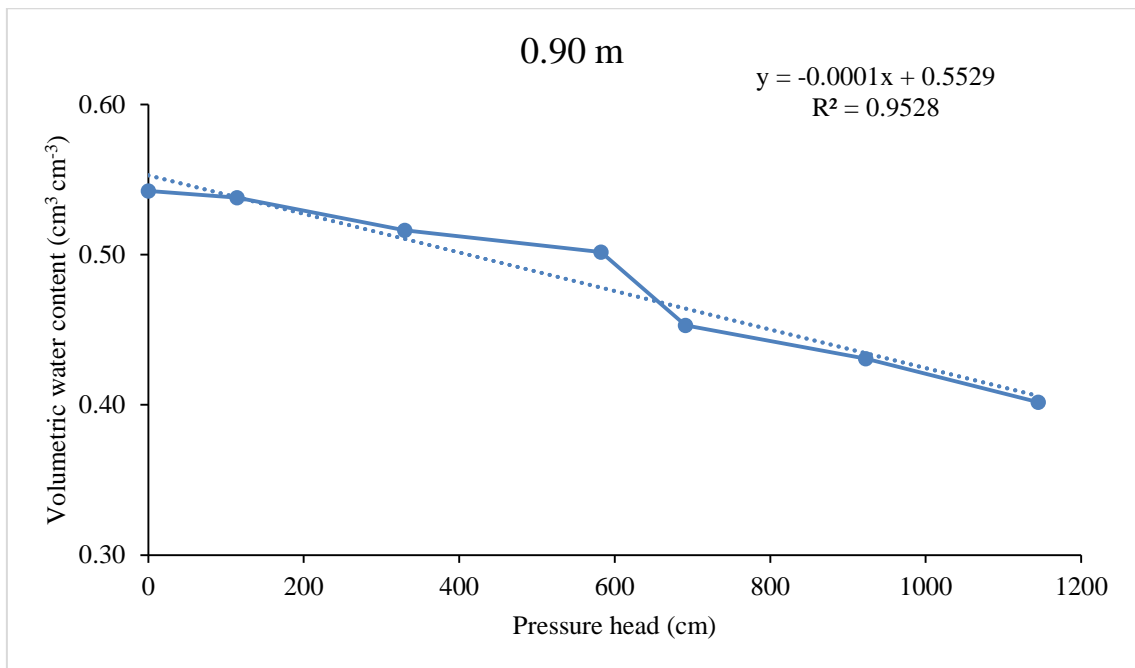
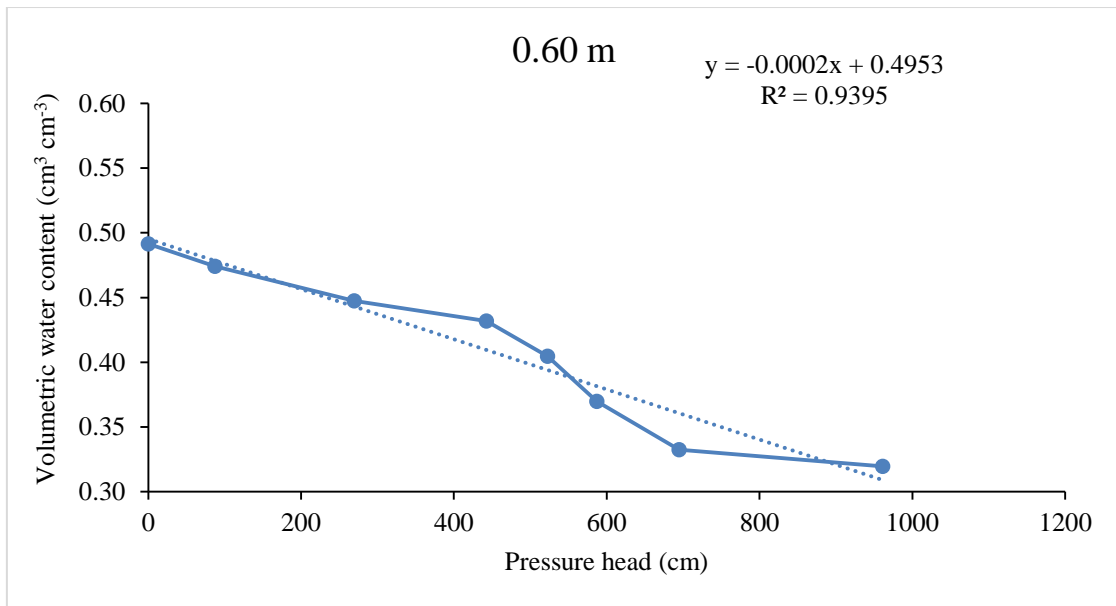
Other graphs showing the variation in weather variables recorded over the 2015/16 season at Swayimane are presented next. These include air temperature, solar radiation and wind speed.



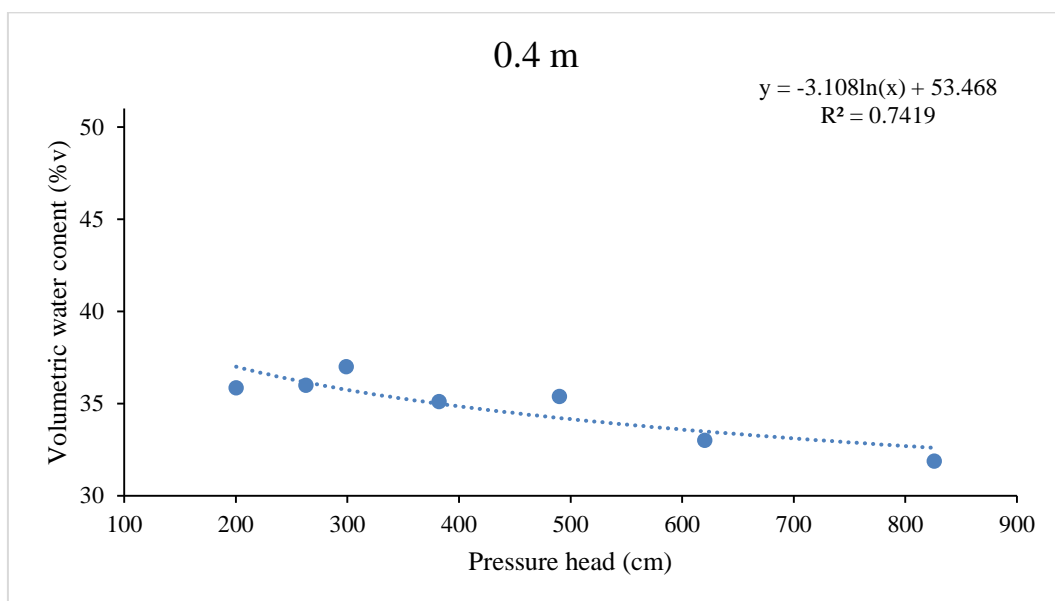
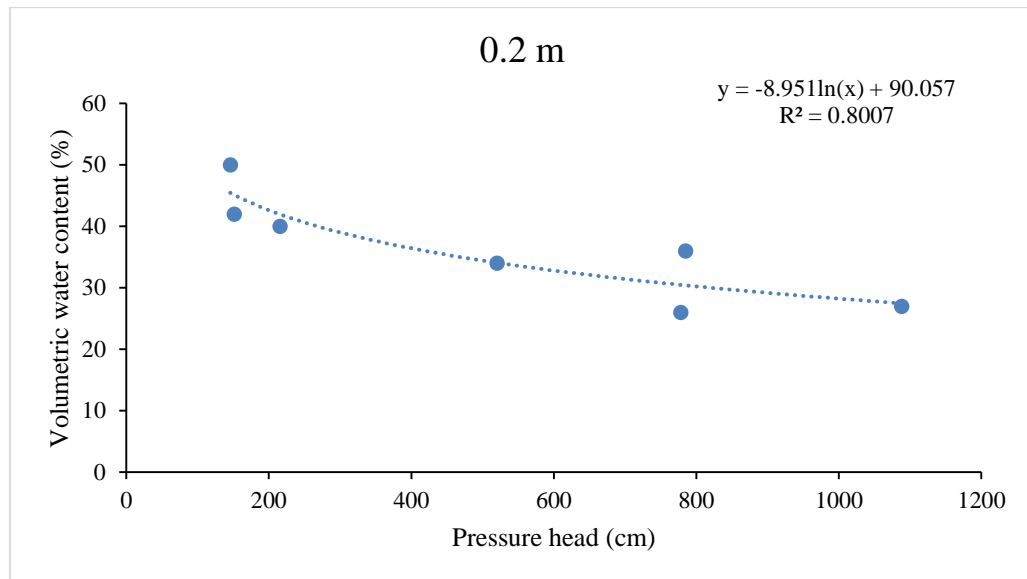


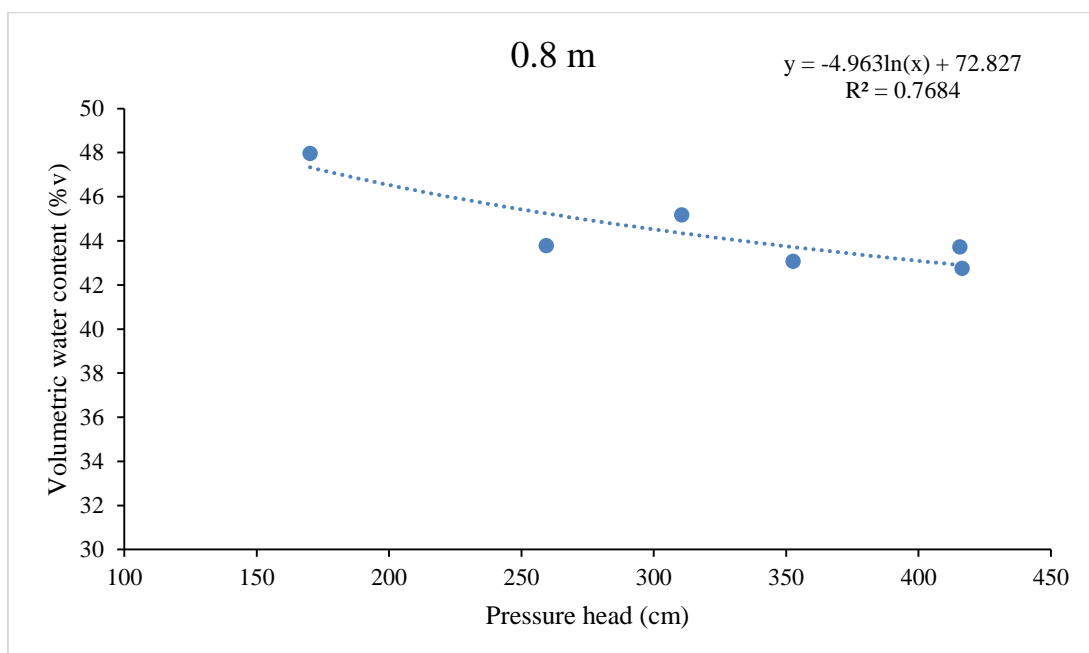
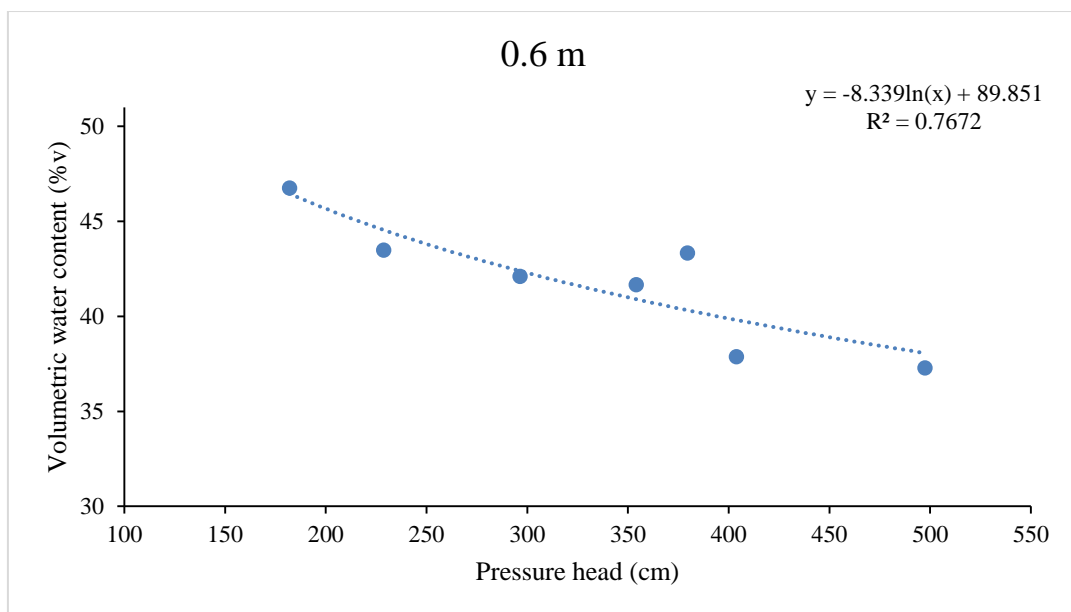
Appendix 7: Soil water retention curves for different soil depths as obtained from drainage pit where $-1 \text{ kPa} = 10.2 \text{ cm}$. (the dotted line is a trendline whilst the solid line represents actual measurements)

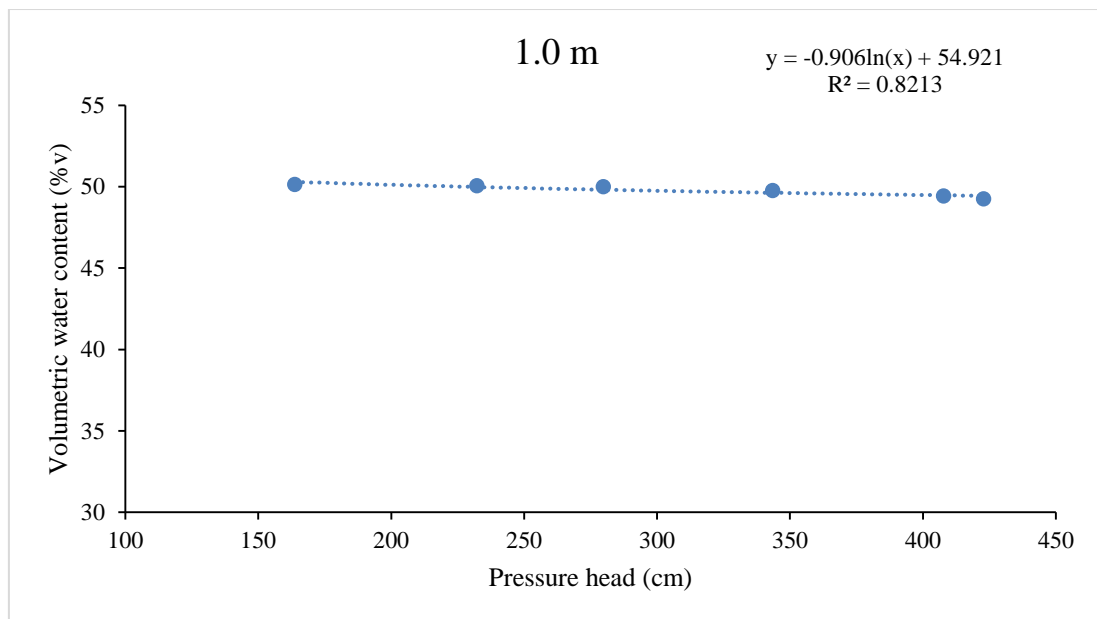




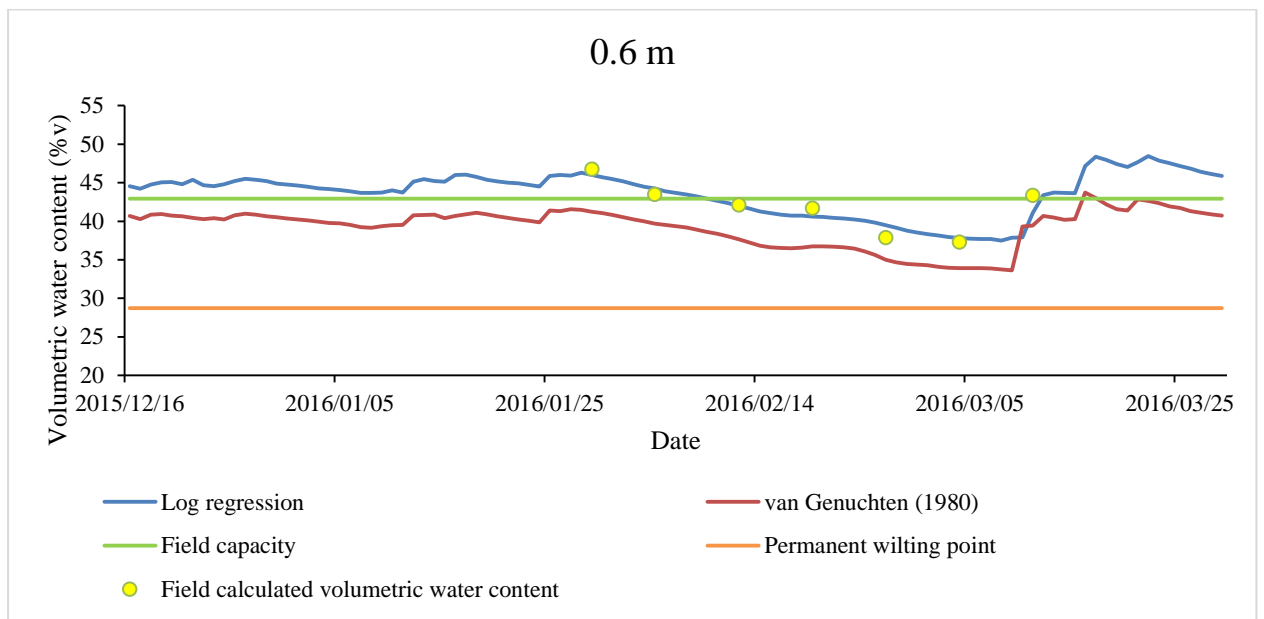
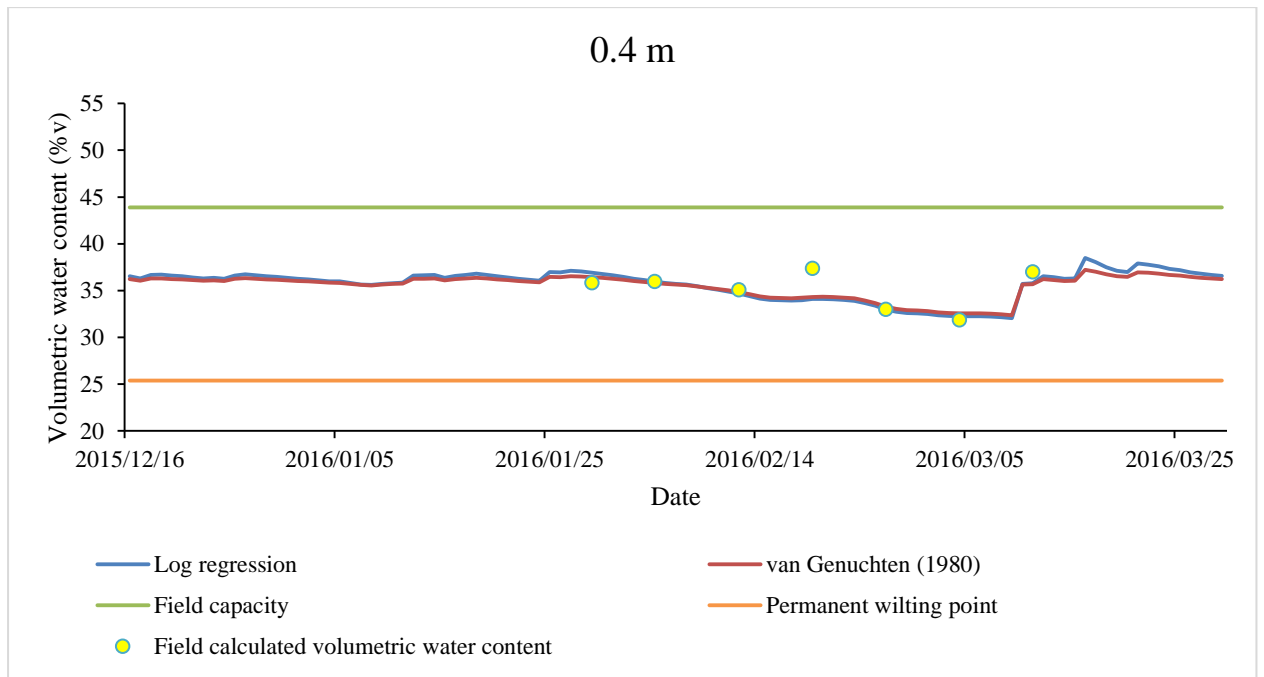
Appendix 8: Regression curves obtained from gravimetric water content at various soil depths (dotted line represents the trendline)

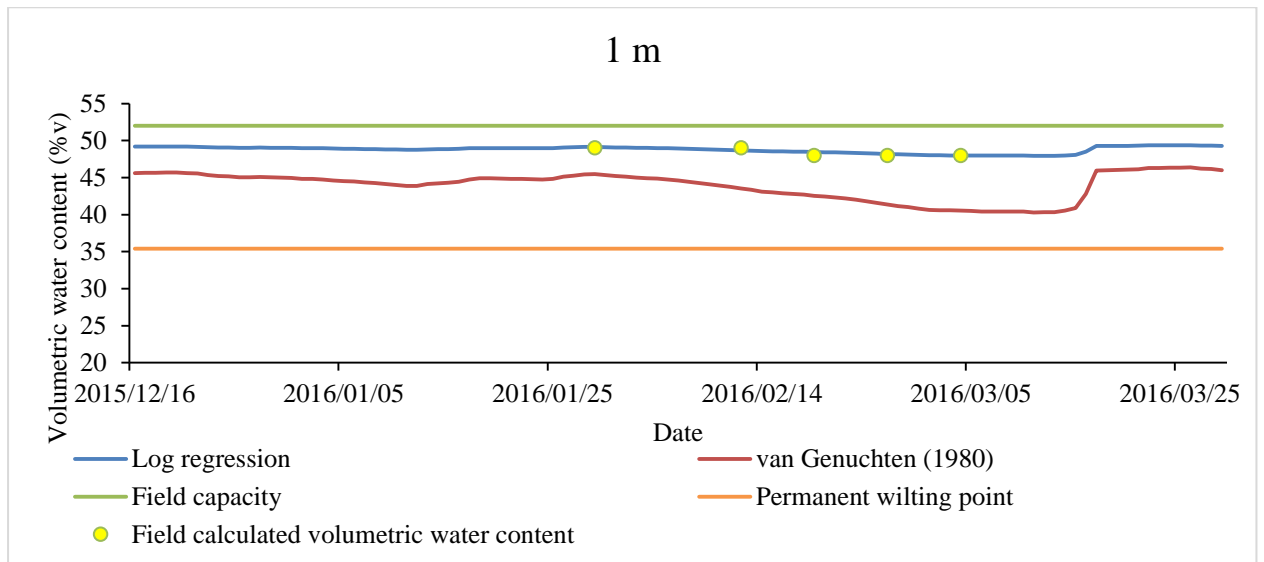
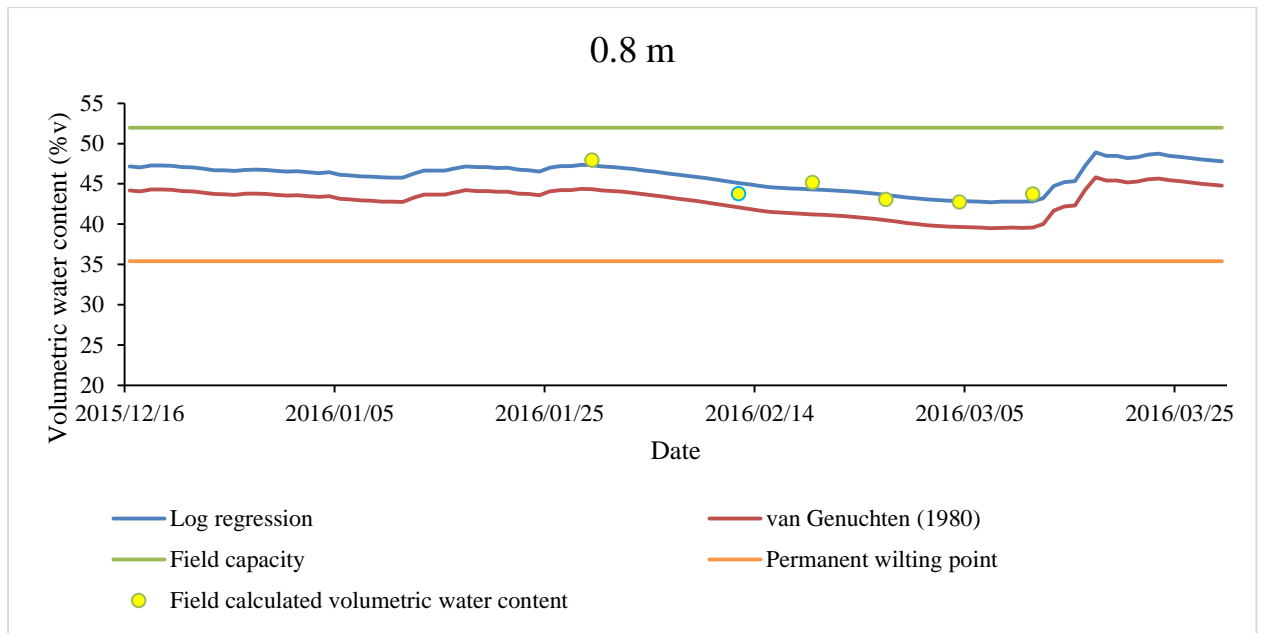




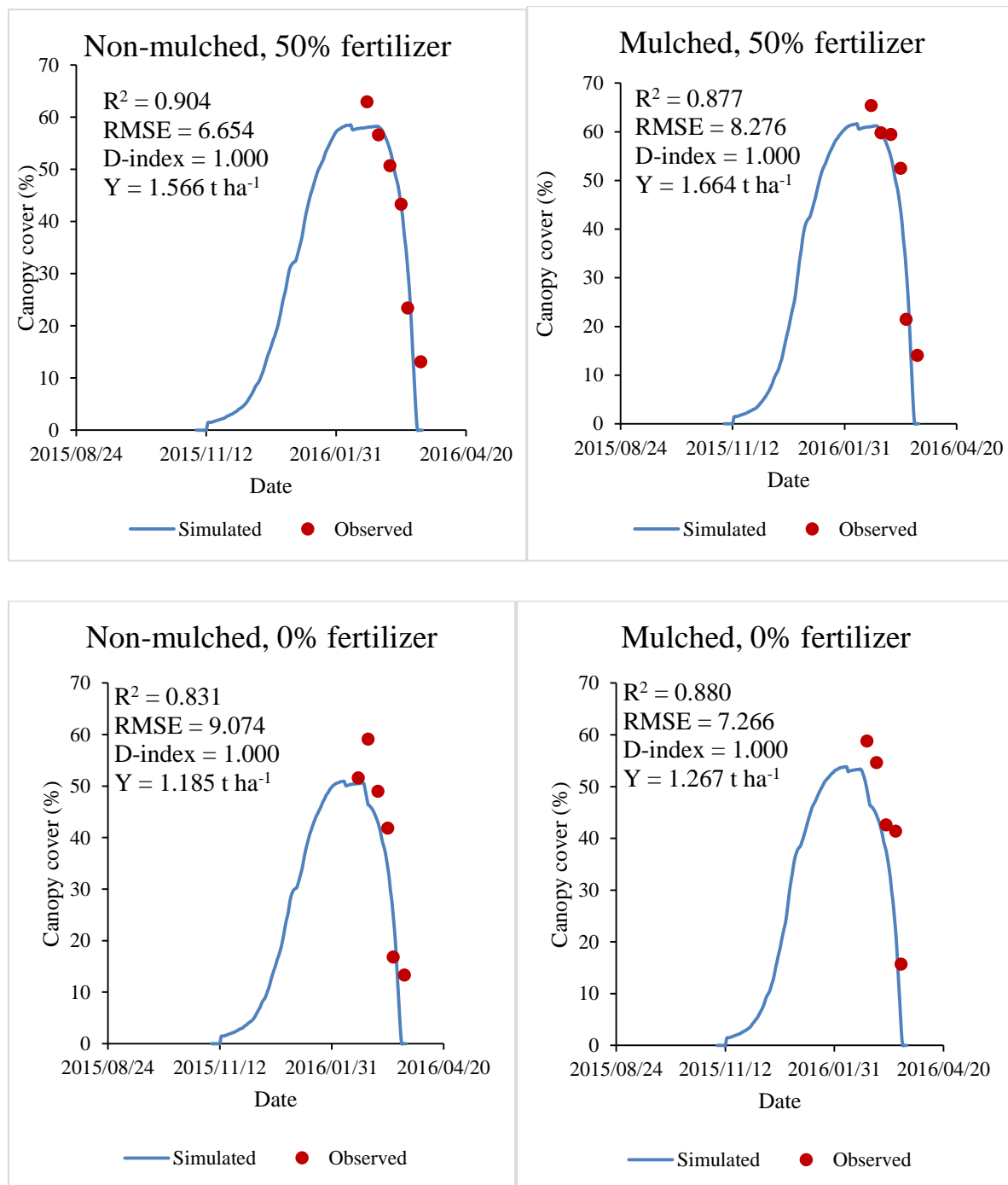


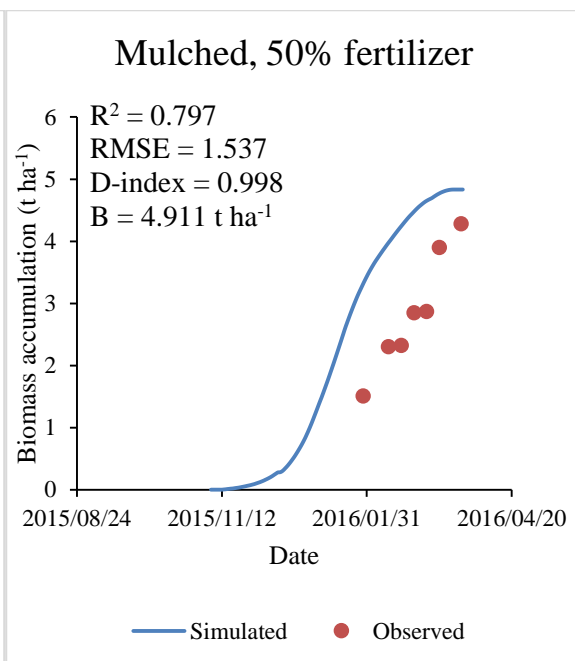
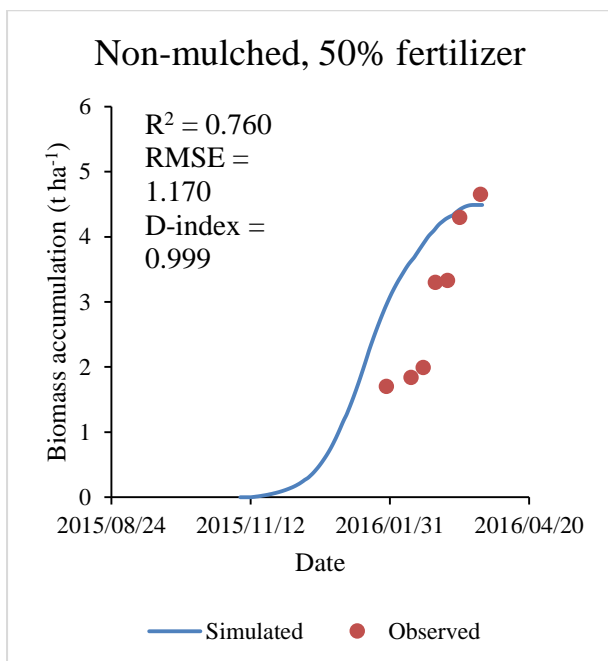
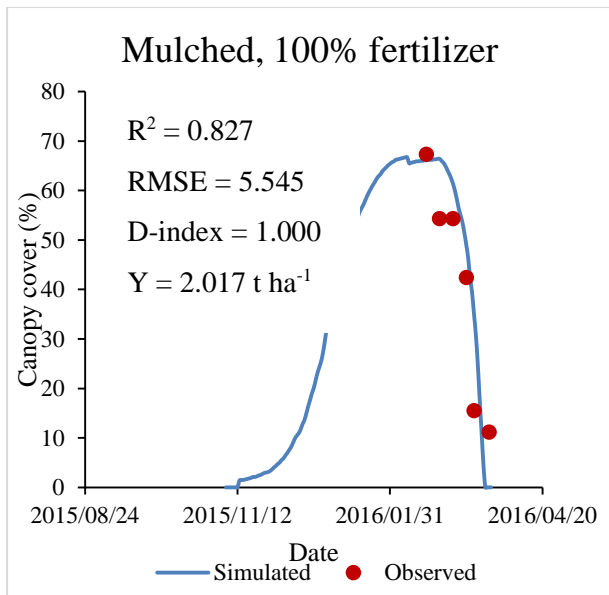
Appendix 9: Comparison of regression curves and van Genuchten (1980) equation to estimate volumetric water content

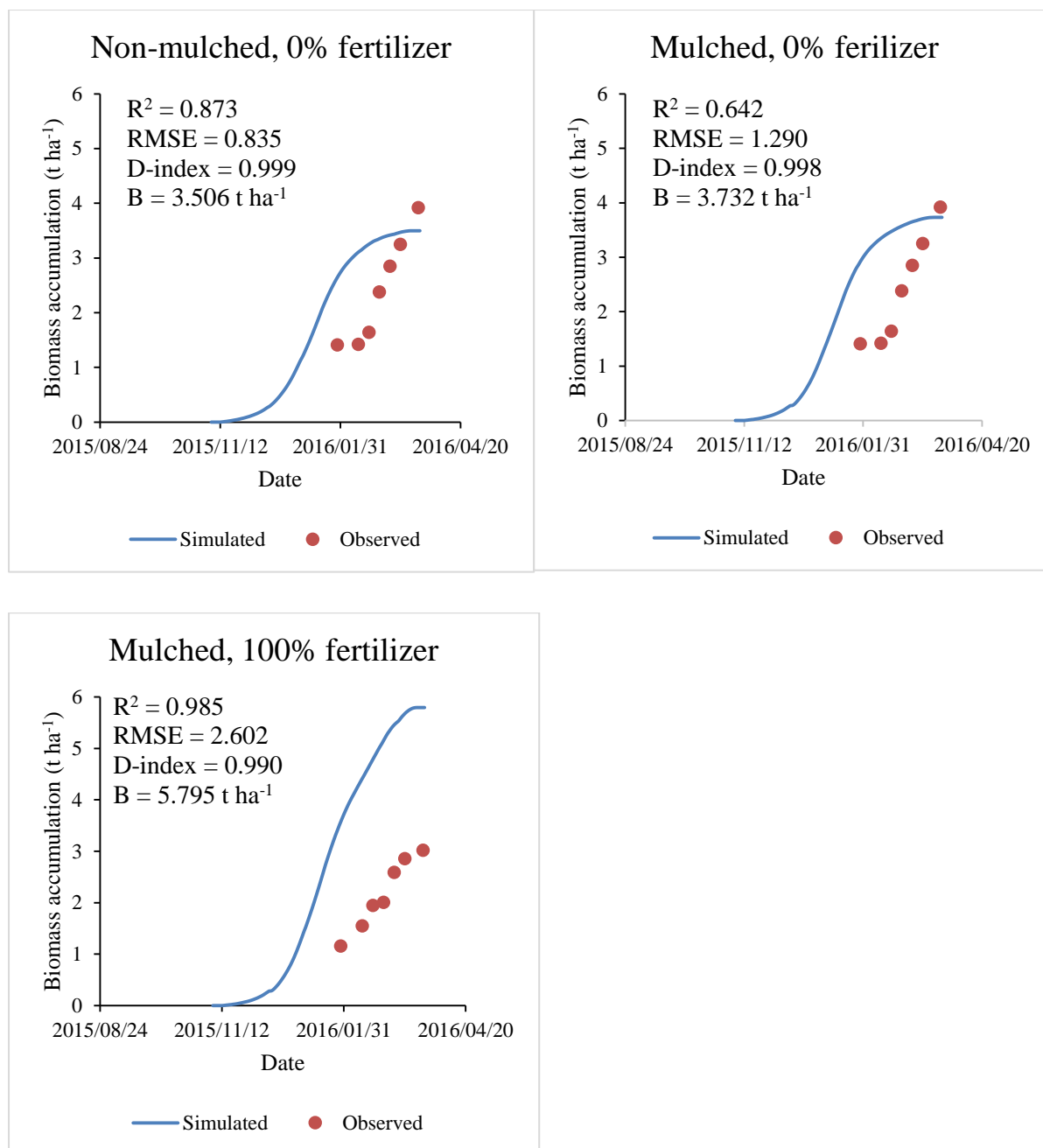




Appendix 10: Model evaluation by comparing observed and simulated biomass and yield in AquaCrop







Appendix 11: Comparison of estimated profile water content to simulated profile water content by AquaCrop

